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Ultrasonic NDE system: the hardware concept

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Introduction

Increasing number of ultrasonic applications reflects the potential of this method. As broader is the range of areas involved in ultrasonic measurement, the more essential becomes the question of a universal concept of the equipment for generating and acquiring the ultrasonic data. Ideas and problems met here we would like to share in this publication.

The ultrasonic non-destructive evaluation system basic equipment used for ultrasonic data extraction is shown in Fig. 1.

The ultrasonic transducer is excited by on electrical pulse and transmits the ultrasonic pulse to the media under investigation. The ultrasonic pulse travels in the material and is reflected, refracted, scattered or transmitted through its inhomogenities. The affected signal is picked up by the same transducer (transceiver mode) or the separate transducer and is converted to the electrical signal. This signal then is amplified, filtered and converted in to the digital form. If necessary, the signal is stored on a disk. The digital signal pre-processing (averaging, smoothing), post-processing or just real - time presentation on screen is performed as A-scan, B-scan or other appropriate image. The transducer can be positioned on the material in any position on the material surface or in water if the immerse scanning is used.

Transducer excitation

An exciting pulse must possess the bandwidth wider or at least equal to the ultrasonic transducer bandwidth one is going to use. Usually, the bandwidth is desired to be wider if the time resolution or spectral investigation is the goal. Fig. 2 shows most commonly considered exciting pulse shapes.

All pulses presented above have the same maximal amplitude and 0.5 level duration (which differs from the duration definition, used in signals theory) of 200 ns. If such a pulse is used for 2.5 MHz transducer excitation the best energy feed is achieved, but the bandwidth is reduced. The positive pulse edge is exciting the transducer and the negative edge is of the same phase. In the case the negative edge is positioned in such a way that it is of opposite polarity to the excited transient, the ringing time can be significantly reduced, but energy feed will be sacred. Therefore the pulse generator with a variable pulse width is very suitable for pulse bandwidth programming. If the pulse duration can be digitally controlled and is the stable, repeatability of measurement results is increased. It must be noted here that the stable duration is of great desire, because even slight variations of the pulse width can cause rapid changes in generated pulse energy. This will definitely lead to the unwanted artefacts. When avalanche devices are applied for generation of sharp front pulses, the avalanche creation uncertainty can lead to such problems. The same situation can occur if RC circuitry or IC ramp generator is used for a duration formation with no special precautions taken for an add-on noise.

Turning back to the pulses presented above, it should be noted that all they have the same maximal amplitude. The active elements for generation of such signals will have the same working voltage. The best spectra would answer the pulse shape choice question. For this reason we have presented the absolute spectral densities of pulses in Fig. 3.

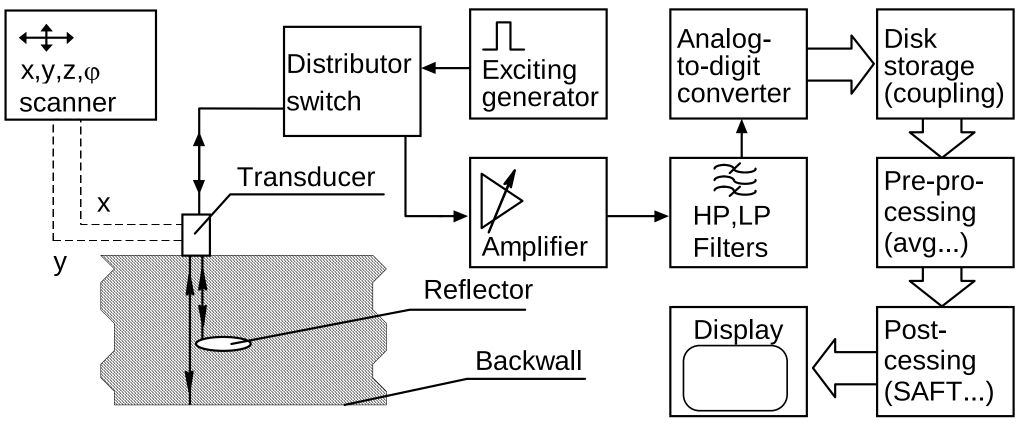

Fig. 1. **Ultrasonic NDT system equipment diagram.**

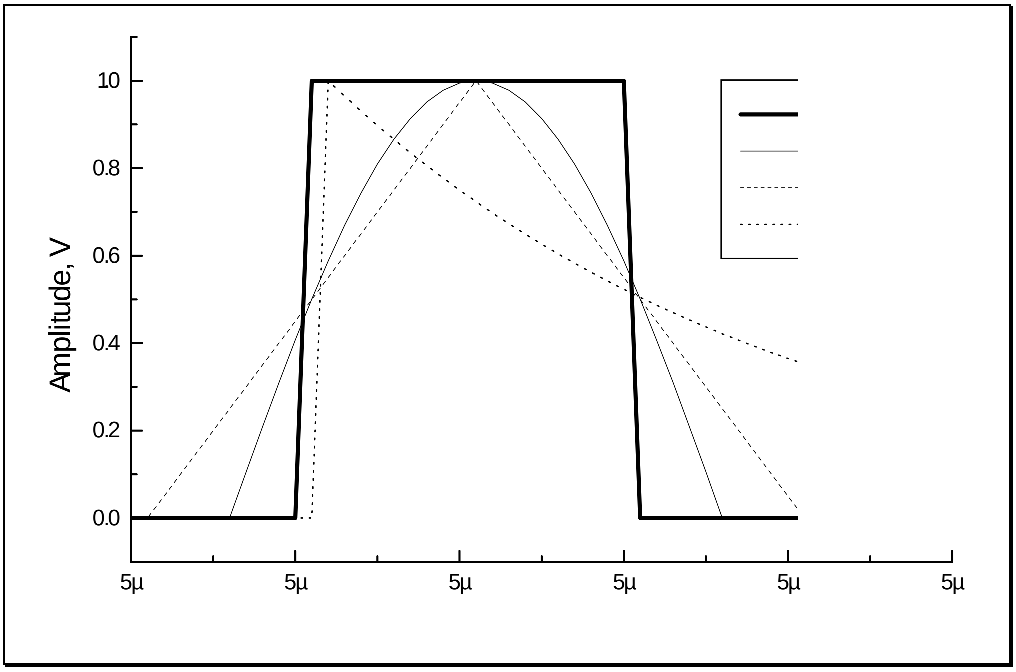

Fig. 2. **Common exciting pulse shapes**

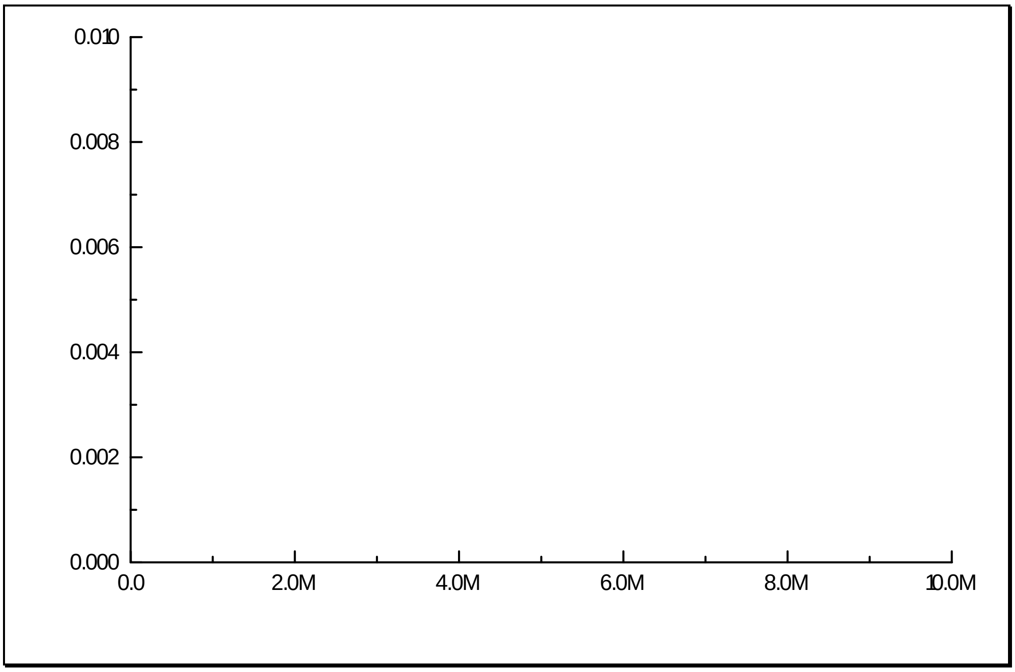

Fig. 3. **Spectral density of common exciting pulse shapes**.

By investigating the spectral densities of the pulses mentioned, comes the conclusion that the rectangular pulse is best matching the bandwidth and the efficiency requirements for 2.5 MHz transducer (2.5 MHz transducer frequency implied a 200 ns pulse duration choice $\tau=1/(2f)$). The triangular and the cosine pulse has smaller skew rate requirements, hence in some cases might be more attractive. It must be noted that the sharp pulse transition time limitations will add the additional decay $1/f$ on all power spectra. Bearing this in mind and also taking into the account that much wider exciting pulse frequency range might be necessary, the voltage step function comes out as a possible candidate. For the comparison, 20 ns duration the exponential and the rectangular pulse spectra are presented in Fig. 3. The step function or the exponentially decaying pulse is easy to generate. They can be generated using one active element with a sufficiently high speed and there will be no necessity to care about saturation of the active element. Therefore, the rising edge will be much sharper. In the case of the rectangular pulse, active elements saturation is limiting the switching speed - care must be taken to saturate the switching element in order to be able to switch it off immediately. Circuitry in Fig. 4. is a demonstrating the single stage capable of

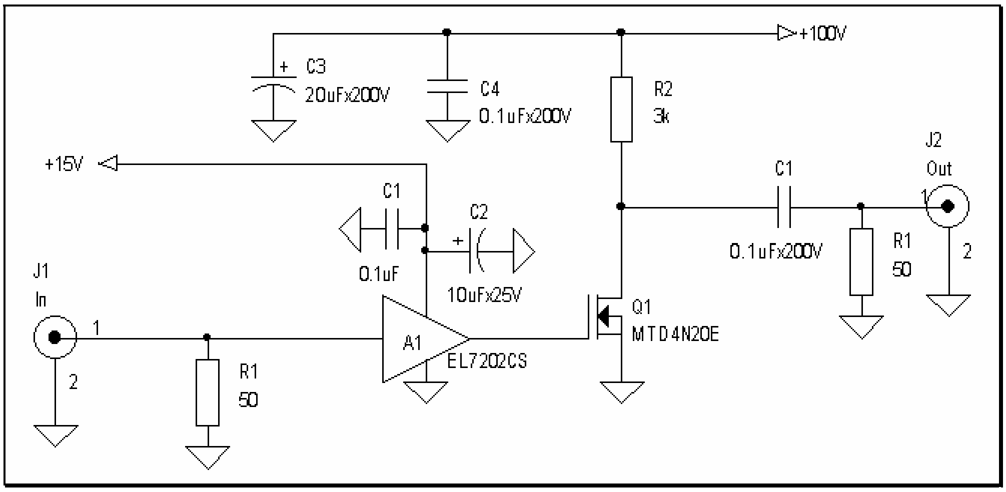

Fig. 4. **Simple exciting pulse generator**.

excellent performance for excitation of the transducers of up to 100 MHz. It must be noted that all the components are recommended to be of the surface mounted type, a low inductance and the sufficient ground plane on printed circuit bard must be produced.

The generator presented has deficit of the energy given into transducer, sinceit is driven by the step function. Asit can be seen from Fig. 3. the voltage step spectra is smooth, so it might be attractive to be exployted for the wide bandwidth transducers excitation. But the short duration rectangular pulse is capable to produce the sufficient bandwidth with a higher efficiency (note the spectra for the narrow rectangular pulse in Fig. 3). The generator presented in Fig. 4 with proper application of a voltage follower after it and some minor changes of the components can be used to generate the rectangular pulses.

To conclude, the pulse generator, producing the rectangular pulse looks as follows: the stage contains two switches, one responsible for fast pull-up and another for push-down of the output voltage. In order to achieve the high skew rates, the generator output impedance is kept as low as possible. This induces other problems:

1. The impedance of the cable, connected to a transducer usually is 50Ω, so the impedance mismatch will be causing the multiple reflections in the cable, especially if the transducer impedance is not matched to the cables.

2. After the exciting pulse has been sent into the cable it is desirable to disconnect a generator from the line, because the low output impedance will be damping the received pulses.

Despite the multiple attempts to employ the 50Ω RF amplifiers, the special switching networks, which were more or less successful, we consider this problem still open.

As the separate case, the special waveform generation circuits can be mentioned [1,2,3]. These are employed because of two possible reasons:

1. If a high pulse energy is required, then the complex signals are of good choice. For instance, the phase manipulated signal will pertain high energy, inherent from the CW signals, but will maintain the excellent temporal resolution, obtained after the signal compression. It is especially attractive in the air-born ultrasound applications, where high surrounding noise level and large attenuation are present. A high signal-to-noise ratio (SNR) can be achieved with such signals.

2. Using the signal post-processing, a signal bandwidth/ temporal resolution can be improved. But because of the insufficient signal level at the frequencies to be restored, the noise becomes prevailing here, so unwanted artefacts are created. If the exciting signal is precompensated for the frequencies, missing in at the received signal, the better SNR is achieved. Possibility to generate an exciting signal of any shape offer even a more sophisticated solution - instead of performing a signal deconvolution after receiving it, the exciting signal can constructed to have such a frequency and phase content, that the received signal is already deconvolved. Such an approach allows to save the processing time and improve the SNR.

The possibility to have the programmable exciting pulse delay offers additional advantages. The closest application for such a feature is the electronical steering of ultrasonic beam, when the ultrasonic transducer array is used [3,4]. Another application, offering the improvement in the sampling rate will be discussed further.

Transducers

Closer analysis of the transducers design requires wider publication, besides, this topic was already covered in numerous publications. Here, we just mention the impedance matching problem. A simple transducer equivalent circuit can be presented as the lumped parameters circuit, consisting of the serial connection of the capacitance and the inductance, presenting the mechanical vibrating system, and the capacitance connected in parallel, presenting the capacitance of the piezoceramic piston. This circuit is valid in a vicinity of a main resonance. Actually, the transducer has the multiple resonant frequencies. The terminated coaxial cable can be used as an equivalent circuit of the transducer electrical behaviour. The transducer input impedance can be adjusted using an additional coil connected to the transducer. Improvement of the bandwidth can be achieved in the same way, but for a better matching, more complicated circuitry is required [3,5].Usually, the cable delay is longer than the pulse transient, so the exciting signal bouncing inside the cable is jamming the preamplifier channel in the transceiver mode a significant time. It can be seen as the DC level floating or a parasitic reflection popping-up after the exciting pulse.

A special attention must be drawn to the unfocussed transducers. Because of the wide wave front these require a sufficient shielding and the matching coil to reduce the noise level at the high gains which are usual for such applications. Passing the cable through the high permeability ferrite bead can also reduce the induced noise level significantly. Also, special precautions on the preamplifier shielding construction must be taken here.

Receiver/preamplifier

The receiving preamplifier [6] performs several tasks:

1. It has to have the low noise level and to amplify the signal 6-20 dB.

2. It has to filter the noise at the frequencies which are definitely out of the employed frequency range.

3. To suppress the high excitation voltage if the transceiver mode is used.

The conventional circuitry applied to suppress a high voltage comprises two opposite diodes clamping into the ground, preceded with the 100-300Ω resistor. Sometimes, a small inductance can be applied here and a capacitor connected in parallel with the diodes. Such a circuit has two main disadvantages:

- due to a large exciting pulse energy, diodes accumulate a large charge amount, which latter is stuffing the channel;
- because of a non-linear character of the diodes, they distort the useful signals also, what later is causing the additional artefacts in signal processing;
- if a high efficiency transducer is used, it can produce the voltages greater than a diode threshold voltage.

Employment of the fast switching SCR/diode based circuitry with a adjustable threshold solve the problems at the acceptable level. An attractive choice is the two-terminal circuit protector offered by MAXIM. Placed in series with signal lines, each two-terminal device guards sensitive circuit components against voltages near and beyond the normal supply voltages. These devices are voltage-sensitive MOSFET transistor arrays that are normally on when power is applied and normally open circuit when power is off. When signal voltages exceed the threshold, the two-terminal resistance increases dramatically, limiting fault current as well as the output voltage to sensitive circuits. The protected side of the switch maintains the correct polarity. There are no "glitches" or polarity reversals going into or coming out of a fault condition. Unfortunately, the available versions offer just ±40 V of the operating range.

Still, the impedance mismatch caused ringing problem remains, which can not be solved by such circuits. If the low impedance switch is connected close to the transducer, the exciting pulse bouncing in the cable and the transducer reverberation can be cancelled by opening this switch. As it was mentioned above, the exciting generator can be designed to have a low output impedance. So, this impedance can be employed for dampaning. After the desired time has passed, the generator low impedance has to be disconnected from the transducer (if the transceiver mode is used) in order to let the reflected signals pass to the preamplifier.

Filtering

The filters block is used to adjust the system bandpass range to the transducer, to reduce the system noise and to meet the Nyquist sampling criteria. There is no single recipe what filters should be applied here - it depends on the application. If the phase sensitive processing is to be used, the filter should have as flat phase spectra in the bandpass region as possible, so the Bessel and the Butterworth filters are closest candidates. But this implies less steeper frequency response of the filter. If the phase information can be compensated during processing (which is easily implemented in the digital systems) or phase response is not of much importance, the Chebyshev or the elliptic filters can be applied in order to have the better frequency response steepness at the cutting frequencies. The switched capacitance filters are not recommended in this case. The active RC filters offer cheaper solution, but are of the limited frequency range. The LC filters offer the better SNR, but have large dimensions and require woven elements. Combination of the RC at low frequencies and the LC filters at the higher frequencies can be a possible choice. From the user point of view digitally programmable filters are of a great profit - the signal bandwidth can be adjusted by the software.

Main amplifier

The main amplifier is responsible for the major gain contribution. Thanks to the electronics manufacturers achievements here, one has a wide choice of the programmable amplifiers to employ up to 100 MHz. The gain can be programmed with the 0.1 dB accuracy with a control speed 40 dB/μs [7].

We distinguish two amplifier types - the static and the dynamic amplifier. The gain of the static amplifier remains stable during one A-scan acquisition or even the whole scan time. The possibility of the digital gain control allows for the signal dynamic gain compression as it will be discussed further. The dynamic gain amplifier gain is varied during the A-scan acquisition time. Sometimes it is called time variable gain (TVG) amplifier. Thanks to the digital TVG control, the gain for the every time instant can be known, so later, if necessary can be removed in order to get the proper signal processing results. The dynamic gain is mostly dedicated for the signal decrease versus depth compensation. The decrease can occur because of various reasons - mostly a beam spreading is influencing it, but the attenuation in material is not of least importance too. In the composite materials scattering is the prevailing reason of the signal level degradation. The signal amplitudes can vary in a 90...120 dB range.

Table 1 **Number of bits required for A/D conversion**

Input signal dynamic range (dB)	Number of A/D converter bits
20	5
40	8
60	11
80	15
100	18
120	21

The frequency range used in a conventional NDT usually varies from 0.1 MHz to 25 MHz. In the digital NDT systems, such ultrasonic signals must be sampled and digitised. This requires a high sampling frequency and a large number of quantization levels of A/D converters. The instrumentation used for such purposes cannot usually satisfy both requirements at the same time. On the other hand, due to the finite linear range of amplifiers, detectors and the other analog electronic units, the signal amplitude must not exceed the maximum allowed level. On the contrary, it can cause an overload of the amplifiers and a significant loss of information.

Usually, the levels of the received signals are not known in advance. Therefore, each time when starting the NDT of a new object, it is necessary to adjust the amplitude range of received signals to the linear range of the instrumentation. Usually this is done manually by performing the multiple scans of the object. It is a time-wasting and boring procedure for an operator. When an inspection is performed in a dangerous environment, for instance in the nuclear power plants, the time needed for testing should be as short as possible. So, it is highly desirable to develop an automated NDT procedure which will allow, in the ideal case, to obtain 2D ultrasonic images during a single scan without *a priori* knowledge about the features of the object under investigation.

The adaptive gain control we have developed and implemented in our systems offers a compression of a signal dynamic range which allows employment of the smaller bit number A/D converters [8]. The essence of the method is based on the assumption that an ultrasonic signal level is not changing rapidly from one scanning step to another. In order to satisfy the Nyquist sampling criteria for a spatial information sampling, scanning system must fulfill this requirement. Bearing this in mind, one can predict the next step amplitude, expliting the measurements previous steps. If the digital gain control is incorporated in the system, the gain correspondence to the control code can be easily established. Then, by knowing the previous measurements amplitudes and the gain level at which they were obtained, one can predict the absolute value of the next measurement. Of course, it will be a rough approximation, but sufficient enough in order to set the gain before next measurement is performed. The gain is set at such a level, that the A/D converter dynamic range is exploited in the best way - i.e., the maximal amplitude of predicted signal is set to be close to A/D conversion range limit. Together with the samples from the A/D converter, the current gain level is stored on the disk or other media. So, when data is restored after the measurement for post-processing or imaging, the absolute signal values can be restored to by taking the current gain values into account. In addition, the signal measurement can be performed in one shot, so multiple scans and gain adjustments chain are not necessary.

Also, the digital gain control allows for an interactive gain set-up if the adaptive gain control is not used. The user can see an immediate result obtained after the gain change.

Scanner

The scanner or positioning device might have two major configurations:

1. Automated scanner. The transducer is positioned into desired position automatically, using the analog, step or piezomotor drivers. The track of it’s position is either measured counting the driving pulses, supplied to step or piezodriver or measured using any of wide variety of available position tracking devices. Separate case is the electronical beam steering, either using the linear or two dimensional arrays.

2. The manual scanner. The position of transducer is chosen by an operator by moving it manually into the desired position. The position readout varies from the optical tracing, introduced by Sonomatic Ltd., to special wheels or the belts systems offered by Panametrics or robotics arm follower employed by ALOCA.

We do not plan to present the coverage of scanning methods or variety of the equipment. We shall just mention some features important from the acquisition point of view. In order to obtain a high measurement speed, especially if large volumes have to be covered, the transducer positioning from one desired position to another should be as fast as possible. But this automatically implies the positioning error. Stepwise movement should suggest a higher achieved accuracy, especially if the step motors are applied. The step motors also offer better efficiency of a driving circuitry, because of a simple construction of the driver. However using the step motors implies a discrete noise in determination of the position. Therefore, the quality of the positioning system as a resonant circuit should be kept as low as possible. Usually, this is done by using high hold torque motors or applying the gearbox. Also, the post-scanning delay should be introduced in order to let the scanning head to settle down. The gearbox is implemented in order to reduce the step size and increase the moving torque too. But the gearbox can cause a hysteresis between movement back and forward. Besides, such a useful feature of the step motors as hold-off is no longer available then. Applying hold-off, the step motor driving current is removed. Then, the scanner head can be positioned manually into a desired position. This approach offers more natural positioning interface for small systems, when an initial positioning is applied. By counting the pulses induced at the step motor output tracking of manually adjusted position can be performed. In the case when just a relative scan position is important, it is not necessary. Since the step motors offer a limited single step angle, the gearbox application for a step size reduction seems self evident. In the case when strong torque is not necessary, there is a way to reduce the step size without the gearbox. We have implemented the gearbox-free driver for the step motors. Instead of applying 4 phase bipolar control of a step position, we supply the sin/cos stepwise current function into driving coils. If number of steps on sin/cos function is 4, then such a driver does not differ from the conventional step motor driver. If number of steps is greater than 2^n , the step size is reduced by the same number. Of course, the same approach can be used even the step motor has a gearbox.

A/D conversion

Using the A/D converter, a signal is sampled in the time domain and it's amplitude is quantized. The quantization influence was discussed earlier [8]. The signal sampling can be presented as multiplication with the *shah* function III [9]. The sampled signal spectra will be periodical with a period of the sampling frequency harmonics. Because of a discrete presentation of the spectra in a computer, the signal investigated using the DFT is also interpreted as periodical. The circular convolution effects must be avoided. Everything said above puts some limits when setting the sampling interval. It must be chosen to have the sufficient zero-padding at the beginning of the gate and at the end. The sampling usually is performed at some particular depth, therefore we introduced a possibility to shift the A/D converter buffer memory address to any depth. Such a concept allows to sample virtually any depth of the material, using the relatively small capacity (2-32 kb) buffer memory. For the analog gating, if necessary, the TVG generator code sequence can be programmed accordingly. For the further processing, in order to avoid the circular convolution influence in the time domain, the artificial zero- padding can be added to the sampling array.

In conventional acquisition systems a sampling process is synchronised using an external trigger or using a particular input signal level and front. Since the time of signal arrival in not known in *priori,* this seems natural. In the ultrasonic systems with an active excitation, the time of the arrival can be predicted. In such a case the exciting pulse generator signal can be used to synchronise the acquisition process. But one has to bear in mind that sampling process has a discrete character. This means, that despite the trigger signal has arrived into the sampling unit, it has to wait for the synchronisation period front. If no special precautions are taken here, acquisition of repeated ultrasonic signals (for instance, for averaging purposes) will contain a jitter noise, which can significantly distort the measurement results. Furthermore, even during the scanning process, the front of reflections from smooth surface will have stairs on it. If all system blocks are "in one hands", the synchronisation process can be reversed upside down. The sampling block can initiate the exciting pulse generation trigger signal, synchronised to it's internal clock. In such a case, there is virtually no jitters in the received signals. Some commercial A/D conversion cards offer the internal trigger function. If a digital oscilloscope is used, implementation of this feature is more complicated. As it was mentioned above, in discussion about exciting generators design, the generator can have the possibility to vary the exciting pulse shift relatively to the start trigger signal. If the adjustment step is stable enough, the equivalent time sampling (ETS) can be obtained here. In conventional acquisition systems a special synchronisation schemes are employed in order to have the good synchronisation with respect to the signal arrival time. To produce the ETS phase shift, an active excitation ultrasonic system can have the ETS at virtually no cost, if a corresponding generator design is present.

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References

1. **K. Ohta and Watanabe** Ultrasonic flaw detection using a synthetic waveform generator and finite impulse response filter (FIR-filter)//NDT & E International.- 1997.-Vol 30. No.6.- P.405.
2. **U. Grimaldi and M. Parvis.** Enhancing ultrasonic sensor performance by optimization of the driving signal// Measurement.- 1995.-Vol 14.- P.219-228.
3. **V. Sukhorukov, E. Vainberg, R. Kaþys.** Non-destructive testing. Imaging and automation of testing// Vysshaja shkola.-Moscow.- 1993.- Vol 5. Ch 5.
4. **A. Lovejoy, P. Pedrick.** et all A novel 8-bit ultrasound phased-array controller for hypertermia applications// Ultrasonics.- 1995.-Vol. 33.- P.69-73.
5. **D. W. Fitting, L. Adler.** Ultrasonic spectral analysis for non-destructive evaluation// Plenum Press.- New York.-1981.
6. **A. D. Armitage, N. R. Scales** et. all An integrated array transducer receiver for ultrasound imaging// Sensors and Actuators A: Physical.- 1995.-Vol. 47.- P.542-546.
7. **D. I. Hughes and F. A. Duck** Automatic attenuation compensation for ultrasonic imaging// Ultrasound in Medicine & Biology.- 1997.- Vol. 23.- P.651-664.
8. **R. Kaþys and L. Svilainis.** Analysis of adaptive imaging algorithms for ultrasonic non-destructive testing// Ultrasonics.- 1995.- Vol. 33. No1.- P.19-30.
9. **R. N. Bracewell.** The Fourier transform and it's applications// 2-nd ed., McGraw-Hill.- 1986.
10. **N. Vaitkus, L. Svilainis, V. Dumbrava.** General purpose scanning unit for NDT ultrasonic systems//Proc. of higherschools of Lithuania.- Ultragarsas.- 1993.- Vol. 25. P.88-97.

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Ultragarsinė matavimo sistema: aparatūros projektavimas

Reziumė

Ultragarsinės sistemos naudojamos vis plačiau, ir tai netiesiogiai patvirtina šio metodo privalumus. Kuo daugiau yra sričių, kuriose naudojamas ultragarsas, tuo svarbiau turėti universalią sistemą, kuri galėtų generuoti ultragarso signalus ir surinkti ultragarsinę informaciją. Šiame straipsnyje norėtume pasidalinti idėjomis ir problemomis, kurios susikaupė projektuojant tokio tipo sistemas.

Nuolat didėjanti elektroninių komponentų, kurie gali būti valdomi skaitmeniniu būdu, įvairovė davė stiprų impulsą plėtoti ultragarsines sistemas ir tobulinti parametrus, tuo pat metu mažinant jų matmenis ir svorį. Aktyvaus zondavimo ultragarsinės sistemos, palyginti su įprastomis duomenų surinkimo sistemomis, jei jos suprojektuotos protingai, turi geresnius parametrus kaip tik dėl duomenų surinkimo algoritmo ypatumų.

Laiko ašies virpėjimas gali būti sumažintas palyginti nesudėtingais metodais, strobuojamas duomenų surinkimas gali būti suorganizuotas neįprastu, tačiau efektyviu būdu. Skaitmeninis stiprinimo valdymas kartu su laiko atžvilgiu valdomu stiprinimo keitimu bei stiprinimo kalibravimu leidžia suspausti duomenų dinaminį diapazoną, praktiškai neprarandant tikslumo. Panaudojus tikslų ir stabilų generatoriaus impulso trukmės valdymą, ultragarsinio keitiklio savybės gali būti valdomos. Šie privalumai leidžia tvirtinti, kad ultragarsinės sistemos įgauna geresnius parametrus, jei joms žadinti ir duomenims surinkti naudojamos specialiai sukurtos, o ne įprastinės sistemos.

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