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Design principles for electronic measuring path of ultrasonic tomography robotic system

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Abstract. The paper discusses the requirements introduced to ultrasonic testing for industrial applications including robotic inspection. The specifics of ultrasonic tomography systems development are discussed in relation to the measuring path design. Requirements to robotic scanner are considered. The block diagram of analog component of single channel system of ultrasonic testing is provided.

1. Introduction

Development of advanced ultrasonic tomography robotic system represents complex engineering task engaging solutions from various engineering fields, starting from precision mechanical scanner development, application of advanced hardware components in amplification paths, ultrasonic signal filtering and analog-to-digital conversion, and concluding with implementation of ultrasonic scanning data processing and imaging algorithms based on parallel processing [1].

At present ultrasonic testing is performed in manual and automated testing modes [2]. During manual ultrasonic testing the ultrasonic transducer is moved manually while during automated ultrasonic testing the ultrasonic transducer performs automated movements within the specified program with application of specific mechanical system that is scanner. Significant progress in speed and quality of ultrasonic tomography system performance can be achieved with development of robot data measurement systems enabling to perform in real time mode the primary ultrasonic signals processing including those in ultrasonic multichannel tomography systems.

Equipment designed on the principles of ultrasonic tomography systems as of the promising method of nondestructive testing comprises the following functional units:

- mechanical system enabling movement of the ultrasonic multielement transducer along the specified trajectory near the surface of the object under control;
- electronic multichannel system for amplification, filtering and digital conversion of ultrasonic signals;
- computation system enabling processing, interpretation and imaging of defects spacing in the volume of the object under control.

Analysis of the available on the market final products that enable realization of the functions of ultrasonic tomography systems elements allows to use the major share of the existing finished components; thus lessening the period and reducing the costings for inspection systems development [3–6]. The most significant and quite specific point for the system development is software design. In this way, the process of ultrasonic tomography system development presupposes systemic integration of the above mentioned functional units which represents complex engineering task.

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2. Requirements to ultrasonic testing for industrial applications

The equipment and instruments developed in compliance with corresponding state standards, unified operational procedures and maintenance manuals are to be used for inspections.

Calibration of testing setups and equipment is performed periodically following the schedule set in compliance with the guidelines for these setups and equipment technical maintenance, also stated in equipment certificates and maintenance manuals. The data about periodical calibration and parameters under control is put into the designated sections of the equipment certificates (service list).

Metrological guarantee is realized in compliance with the requirements of the state standards of the Russian Federation: for setups and equipment defined as measuring instrumentation, the pattern approval certificate is issued, while for setups and equipment not defined as measuring instrumentation, the certificate of conformity is issued.

The largest scale enterprises that use nondestructive testing systems such as Gazprom, Russian Railways, Rosneft, Rosatom developed their own industry specific requirements for nondestructive testing procedures. The requirements are set as branch standards determining the scope, inspection intervals and nondestructive testing methods and techniques assigned for equipment and products. Also, the branch standards determine the types of transducers and equipment for ultrasonic nondestructive testing that are recommended for the use in inspection of the given objects under control.

2.1 Requirements to ultrasonic robotic testing

Manual nondestructive testing is known to possess a number of limitations that is low productivity and reliability of inspection, not sufficient results recording, and considerable human factor effect.

Application of instruments and systems of robotic testing partially or completely eliminates these limitations. Mechanical scanning systems widely available on the market of nondestructive testing equipment can be divided into two categories: systems of manual and automated positioning. At that, for both categories there are single-axis scanners as well as two-axis scanners available. Both categories are used for single channel systems as well as for multichannel systems with the transducers based on phased arrays.

Single-axis scanners are used for linear movement of the transducer as well as for the transducer positioning on the circumference. Such scanners are conventionally used for quality control of pipelines welded joints. Scanners to perform manual testing are equipped with encoders of linear and rolling type with high resolution capacity for ultrasonic testing data binding to the measurement point. Two-axis scanners are more often used for radial surfaces inspection, for example, for pipelines corrosion testing.

In case of the automated scanner positioning, the law of ultrasonic transducer motion is set by the computing unit which processes data acquisition during testing. In all the cases, application of single- and two-axis automated positioning systems is limited by the surface configuration of the object under control. For the objects of complex geometry there is the need in individual adjustment of the positioning system or development of custom made solution which together with upgraded software is responsible for ultrasonic data binding to the inspection point and imaging. Further, it is also possible to use robotic manipulators for scanning systems with greater number of degrees of freedom enabling to perform inspection in different dimensions.

2.2 Main requirements to ultrasonic testing instrumentation

The ultrasonic testing systems are characterized by the following parameters:
- absolute sensitivity;
- relative sensitivity;
- ultimate relative sensitivity;
- sensitivity factor;
- testing range;
- assessment of the dead zone;
- nonuniformity of sensitivity compensation within the testing range;
- relative resolution at the pulse edge;

- relative resolution at the occurrence depth;
- the function of the object under control parameters` effect (ultrasound speed, surface curvature and roughness) on deflection of relative sensitivity and error of the depth meter.

Measurements of the mentioned above parameters are performed in compliance with the procedures stated in GOST-R 55809, where standard calibration samples are used as objects under control. Generally these parameters are not specified or partly stated in specifications for flaw detectors and ultrasonic testing systems available on the market. At that, detailed specifications are provided for the parameters of the electronic module (measuring path) of ultrasonic flaw detector for the systems available:

- the excitation pulse parameters – amplitude, pulse leading edge duration, pulse duration;
- maximum sensitivity of the reception path;
- pass band of the reception path;
- amplitude characteristic of the reception path;
- parameters of time adjustment of the reception path sensitivity – maximum/minimum duration of time adjustment of sensitivity, maximum/minimum delay time of time adjustment of sensitivity;
- the threshold indicator parameters – tuning error of the threshold indicator, operation speed of the threshold indicator.

2.3 Specifics of ultrasonic tomography systems development

Ultrasonic industrial tomography is based on pulse-echo method and differs from conventional ultrasonic tomography in two main principles: inspection of the volume within the object under control and imaging of the testing results. While in conventional instruments, solely mechanical scanning of internal structure of the object under control by narrow-beam ultrasound is implemented; in ultrasonic tomography three types of scanning are used:

- mechanical scanning – the ultrasonic transducer is moving along the surface of the object with the input of the data about coordinates of the current location of the transducer;
- electron scanning is performed by physically formed beam of ultrasound phased array;
- virtual scanning is realized by computational method using the set of signals received during probing the object under control by elements of ultrasound phased array.

Different combinations of these types for inspection of the volume within the object can be applied.

Another difference of tomographic instruments from conventional ones is the testing results provision as images of internal structure of material of the object under control. The two dimensional images of plane sections of the object under control (tomograms) are used most often; however, there is also three dimensional (volumetric) imaging of the internal structure of the object. At that, in addition to convenience of the operator`s reading the testing results, images are quite adequate in relation to boundaries and material discontinuity actual location, in many cases imaging allows to measure actual dimensions of material discontinuity and not relative ones.

To receive sufficient volume of the testing data and build reconstruction of the internal structure of the object, single element transducers as well as phased arrays can be used as they allow to receive controlled acoustic field pulse edge.

In spite of all advantages of ultrasonic multichannel testing systems based on multielement transducers, using these transducers is not always feasible or economically viable. Using multielement transducers is efficient and viable to perform inspection of shallow depth which is related to considerably lower level of the excited ultrasonic signal due to small size of individual piezoelements of phased array, thus leading to signal-to-noise ratio decrease. Further, treatment of surface of the object under control is required for using multielement transducers to ensure specified degree of the surface roughness and planeness. This, for example, does not allow inspection of large-dimensional products casted from metals and alloys.

Due to this, using single element transducer to perform inspection of the object under control is more viable. Hence, mechanical scanning is the type of scanning to perform ultrasonic tomography.

In this case transmission and receiving of ultrasonic signals is performed periodically with different positioning of the transducer on the surface of the object under control. In order to perform transmission and receiving signals under various angles it is suggested to use robot manipulator which enables to perform scanning for the whole geometrically complex surface reconstruction.

During simultaneous space-time processing of all signals received by the transducer from all its positions on the surface of the object under control, synthesis of ultrasonic aperture of large wavelength takes place; images of the object internal structure are being reconstructed. At that, the synthesized aperture is virtually (that is after signals` processing) focused in each point of the visualized zone [7]. This method of volume inspection and obtaining its images is called the synthetic aperture focusing technique – SAFT.

3. Requirements to measuring path of ultrasonic tomography system

General equipment specification is applied to measuring path (electronic module) of ultrasonic tomography system. The specification is applied to electronic and automatic equipment, it comprises:
- General provisions.
- Requirements to the system performance specification.
- Requirements to the system technical specification.
- Requirements to electromagnetic compatibility.
- Requirements to reliability.
- Requirements to electric power supply.
- Requirements to design and others.

Measuring path of up-to-date conventional testing system contains not only the hardware component responsible for receiving and measurement preprocessing of signals from the transducers (analog path) but also the digital hardware component which operates measurements. At that, the digital hardware component is practically an integral part of the embedded or downloaded control software realized via control microprocessor or programmable logical circuit. This leads to specification of the requirements not only for hardware but also for software components of the measurement system for the ultrasonic tomography of the intelligence combined robotic system of digital mechanical processing production.

The block diagram for one of the channels of the ultrasonic multichannel nondestructive testing system (Figure 1) comprises blocks which enable the functions of attenuation, ultrasonic signal amplification, filtering and analog-to-digital conversion. This block diagram is partially or completely followed for each channel during the ultrasonic multichannel nondestructive testing system development.

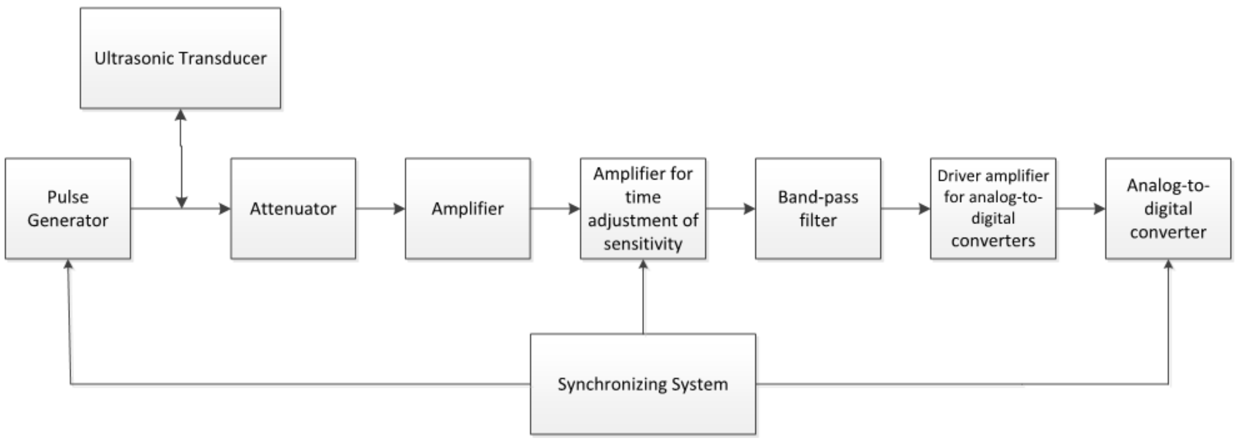

Figure 1. The block diagram of analog component of single channel system of ultrasonic testing.

The pulse generator is intended to generate the probe pulse, and is controlled by the synchronizing system which enables accurate time registration of the probing signal in relation to the scanning scale of A-scan. The input attenuator and amplifier are intended for attenuation or amplification of the echo-signal depending on its amplitude. The amplifier for time adjustment of sensitivity is used to compensate for ultrasonic signal attenuation in the object under control, the amplification coefficient is programmed in relation to strokes generated by the synchronizing system. One of the main requirements to the amplifier for time adjustment of sensitivity is control of the amplification coefficient within the wide range from 40 to 80 dB. The band-pass filter enables the desired signal filtering and noise suppression outside the service band. In case the ultrasonic testing system is designed for ultrasonic transducers with various service bands, it is required that the band-pass filter enables regulation of top and lower frequency of pass band of the band-pass filter. The driver amplifier for analog-to-digital converter (ADC) is actually the input analog-to-digital converter and matches the output resistance of previous stages with the input resistance of the analog-to-digital converter.

A wide range of low-noise high frequency integrated amplifiers and variable gain amplifiers (VGA) allows relatively easy and compactly realize the functions of the preamplifier and the amplifier for time adjustment of sensitivity. The options of designing the block of analog path – the mode convertible band-pass filter come into detailed consideration. The band-pass filter can be made up of passive components or as the active filter based on the operational amplifiers. The passive band-pass filter is easy to realize, however it possesses limitations: signal attenuation, narrow filter order. Active band-pass filters are more complex for realization; however they enable to design the filters of high filter order and, at that, with the specified amplification coefficient. Taking into consideration that during ultrasonic testing systems development ADC number of bits tends to increase, thus, the requirements introduced to the analog path noise characteristics are toughened. The active band-pass filters application seems reasonable, in spite of their sufficient complexity. In both cases when designing the mode convertible band-pass filter the circuit design task of changing the top and lower frequency of pass band arises. There is the option for mode conversion of the passive frequency setting elements or commutation of the entire channels of the active filter.

Conventionally used for these purposes analog switches based on metal oxide semi-conductor circuits operate well within the frequency range up to 1 mHz. Much higher frequencies require application of special high frequency analog codes. The performed analysis of the available on the market components reveals that the most optimal option to develop the mode convertible band-pass filter is using special wide-band amplifiers – multiplexers, which pass band reaches 500 mHz under low distortion factor while the amplification coefficient is normally equal to 2, as they change individual filter channels. The costings and complexity of the circuit design based on amplifiers – multiplexers will be practically the same as for the circuit design based on high frequency analog codes with much higher characteristics of analog path. At that, separate regulation of lower and top frequency of pass band of the band-pass filter requires relatively low costings.

In comparison to analog systems, the main advantage of digital systems of data acquisition and processing is their capacity to change the processing algorithm rapidly, append new functional capabilities when upgrading software responsible for signals processing and imaging. However, as long as ultrasonic signal is analog quantity evaluated as voltage signal which changes in time in the measuring transducer – the key component for digital systems of signals processing is the analog-to-digital converter. When it comes to ultrasonic signals recording, it is essential that the analog-to-digital converter possesses high sensitivity and wide dynamic range for simultaneous recording of significantly different in amplitude signals. In the latest years the world leading producers offered the available now 16-bit analog-to-digital converters with the conversion frequency up to 250 mHz within their products range. This enables new options for development of ultrasonic inspection systems which earlier were equipped with the transducers with the comparable operating speed; however they possessed lower digital capacity which was, as a rule, not higher than 12 bit.

The conventional products range from such leading producers of electronic components such as Texas Instruments, Analog Devices, Linear Technology, Maxim Integrated Products and others contains, as a rule, analog-to-digital converters families based on custom made architecture enabling the required conversion rate and being distinctive in its digital capacity, as, for example, the family AD92xx – AD94xx – AD96xx which is based on pipeline architecture and offers 12 to 16 bit ADCs range with the conversion rate from 125 to 250 million conversions per second. This allows to use once developed design of the printed-circuit board of electronic path of ultrasonic system to program configurations optimized by the set of transducer characteristics as well as in relation to the costings.

Availability of choice from ADC models depending on their operating speed parameters and digital capability is vital; it is also important when considering the real signal-to-noise ratio reached in analog path of the measuring channel. In some cases the effect of the system self-noises reduces to zero the advantages of wide dynamic range and makes 14 bit and higher bit ADCs application senseless. Detailed studies of the electronic equipment self-noises effect lead to toughening the requirements introduced to input circuits design, analog components choice and tracing quality assurance and the printed-circuit board production. At that, in all cases, the higher ADC digital capacity is, the greater capacity loss will take place due to external noises and self-noises effect.

4. Requirements to robotic scanner

Up-to-date production processes and operating practices presuppose design, production and quality control of products using their digital representation. Starting from engineering development of a product in its digital representation, based on which the programme is developed for a range of machines with numeral program control and concluding with end products storage – at any production stage a range of digital models is being designed. The digital models describe the product dimensional components, technological and service properties. In such case, with relatively low costs it is possible to develop a program to control nondestructive testing system which is especially advantageous for geometrically complex objects' inspection. With the digital representation of the object under control available it is possible to use robotic inspection centers characterized by greater number of degrees of freedom. Conventional industrial robots that are in mass use in production processes possess 5–6 degrees of freedom with robot extension up to 1.5 m, accuracy of positioning repeatability is up to 0.1 mm which by the parameters meets the nondestructive testing requirements and considerably increases the capabilities of the systems in case they are used as the basis for automated positioning control device of the transducer. Solutions available on the market from the leading producers of the robotic systems such as FANUC, ABB, KUKA, SCHUNK, Reis, KAWASAKI, KC ROBOTICS, KAMAN CORPORATION and others provide control of their products based on recorded interfaces which enables fast integration of robotic equipment into inspection systems.

5. Design requirements to ultrasonic tomography instruments

The ultrasonic testing robotic system comprises the following individually produced and supplied electrical measuring and control units and modules:

- the unit for measuring acoustic path;
- the scanner control unit (two-axis mechanical or robotic);
- the programmable controller of utility system;
- the control computer of the measuring data acquisition system;
- the server for the measuring data processing and storage;
- uninterruptable power supply;
- network commutator and other modules.

Assorted product range of electronic equipment used in ultrasonic testing system development requires the unified mechanical module construction enabling integration of ultrasonic testing system elements based on unified mechanical structure which will allow to perform maintenance, introduce changes and complements avoiding mechanical processing of individual structural components.

At present the most widely used is the construction of so-called the 19 inch standard rack. Practically all producers of electronic equipment offer their products for assembling in the 19 inch standard rack cabinets and equipment racks. In case of nonstandard equipment the market offers wide range of cases and assembly adjusting accessories compatible with the 19 inch standard rack construction with the option to assemble this equipment with minimum efforts.

The cabinet construction comprises the following main elements: the frame, side frames, doors, cover, guidance elements with holes for equipment assembly. The cabinets provide equipment protection against moisture, dust and dirt, physical damage. The cabinets also serve for protection against electromagnetic radiation. The degrees of equipment protection against dust and moisture are stated as IP code, the cabinets with the degree of protection from IP20 to IP68 are available on the market.

6. Conclusion

Design requirements to ultrasonic testing system are introduced in relation to all its components: measuring path, software, robotic scanning system. At the present stage of the project realization, grounding our opinion on analysis of the characteristics and versions of flaw detectors available on the market, taking into consideration the objective to perform inspection of mold castings with complex geometry it is possible to formulate specific requirements to the system technical specifications and parameters.

The relevance of development of the custom made intelligence combined ultrasonic robotic testing system for digital mechanical processing production is conditioned by the lack of ready-made solutions in the flaw detectors market which would meet the requirements to interfaces open to exchange the measuring data, their transmission capacity. It is also characteristic for closed systems to present problems related to their integration with the automated and mechanization systems provided by the third party producers.

When developing the ultrasonic testing system it is vital to ensure module construction, compatibility with the conventional in-service equipment provided by the third party providers. Thus, it seems reasonable to introduce the requirements to mechanical performance of ultrasonic testing system individual elements using the 19 inch standard rack construction during design and production of measuring and control systems.

When developing the intelligence combined ultrasonic robotic testing system for digital mechanical processing production it is also vital to make provision for increasing the number of ultrasonic testing channels by parallel adding of the measuring path modules. At that, the system expansion is to be sustained by hardware construction as well as by software. This solution application will enable to increase testing speed due to parallel processing, when necessary.

Hence, the developed for ultrasonic testing system software is to meet the requirements conditioned by up-to-date tendencies of information processing technologies development: specification and development based on open software interfaces; client-server architecture; implementation of programming technologies for parallel code processing, multithread processing; implementation of programming technologies for graphic processing unit to perform computation.

Based on the analysis of the available solutions to develop mechanical scanning system for the objects of ultrasonic testing it is possible to conclude that for the objects under control with simple surface geometry it is sufficient to apply conventional two-axis scanners while for the objects under control with complex geometry it is relevant to apply the transducers positioning systems with regard to the object under control. The systems are industrial robotic platforms based.

Taking into consideration the objects under control dimensions, specifics of their production and mechanical processing technologies, it is expedient to choose single channel ultrasonic testing system with robotic positioning of the transducer. This configuration will enable to achieve sufficient productivity of nondestructive testing process as well as increase the testing data imaging efficiency; in case high speed system for measuring data acquisition and processing is used based on single operating station with the GPU accelerators card. This will considerably simplify software development and adjustment as well as it will reduce hardware costings.

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