Principles of the evaluation techniques of the real time non-destructive testing ultrasonic visualization systems

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Abstract

Ultrasonic visualization systems (UVS) for non-destructive testing, which operate in a real time mode, were investigated. Usually manufacturers declare, that such UVS are designed for diagnosis of subsurface defects in solids, composite materials etc. So, the measurement operation must be carried out by UVS in order to get quantitative information about defects size and spatial location. This information has to be presented for the user, who makes a decision about tested object's condition. However, acoustic images, obtained with UVS, do not present the information about defect's size and spatial location. In this case the diagnostic results (or resulting images) of the UVS, are not reliable enough for making a decision. The metrological evaluation of the UVS is required in order to get the impartial and quantitative estimation of the object's test results. Such evaluation is value-adding for the acoustic images obtained with UVS. In this work the tasks for the metrological evaluation of the UVS are presented. The characteristics for the metrological UVS evaluation are proposed. The instrumentalities for determination of these characteristics are proposed and investigated. The methodology for the metrological evaluation of the UVS is presented.

Keywords: real time ultrasonic visualization systems, metrological evaluation.

Introduction

Application of ultrasonic visualization systems (UVS) for non-destructive testing, which are designed to operate in a real time mode, continuously is increasing. In general, the UVS may be grouped according to operation principle, eg., narrow beam systems and wide beam systems.

The basic principle of the first group's UVS is to "look" at the object using a narrow ultrasonic beam and in such a way to obtain the information about properties of the object at that point. So, in order to collect the information about the whole object it is necessary to scan all its surface or volume. There are some examples of such systems [1-9]. The advantage of these systems is that they are relatively universal and may be adapted to inspection of different objects. The disadvantages are the complexity and a time consuming process of inspection. Both these disadvantages are caused by necessity of scanning.

The UVS of the second group irradiate the object by a wide beam and then in some way the reflected field is measured and visualized. The structure of the reflected or backscattered by the object field in general carries the information about the object. In order to obtain this information it is necessary to measure this field avoiding scanning. There are many different techniques for imaging of ultrasonic fields [8], [9]. Some of them have industrial applications. Other techniques are mainly used in scientific measurements. One of the techniques is based on application of an ultrasonic camera, performance of which is very similar to the performance of a video camera. The brief comparison of the obtained information about ultrasonic imaging systems is presented in Table 1.

Table 1 shows that at the moment the most universal imaging system is developed by Imperium. It is also the most novel instrument versus other presented systems, because non-traditional techniques for ultrasonic signal reception and image forming are used. Novel is the ultrasonic sensitive array and image forming in a similar manner as in standard video techniques.

Table 1. **The comparison of the real time ultrasonic imaging systems***

Operating principle	
Imperium [13]	Acoustic image is formed from the signals, received from the ultrasound sensitive array.
Ruhr – University [1-3]	Signals are sent and received by 128 and 128 orthogonal strip transducer elements; multi-channel system.
S. Nakatuska [6]	One transmitter and a number of receivers. The image is formed from the collected signals, which are reflected from the object.
UWASI [7]	Array of receivers collects the signals, which are used to form the acoustic image.
Fingerprint Recognition [4-5]	One transducer operates in TT/R mode

Feature	Impe-rium	Ruhr – University	S. Naka-tuska	UWA-SI	Finger-print Recog-nition
Modes	TT, R	TT	R	R	R
Operating media	water	water	water	contact liquid	-
Real time operation	30 fps	25 fps	13 fps	-	25 fps
Operating frequency	5 MHz reco-mmende d	3 MHz	5 MHz	-	4-16 MHz
Spatial resolution	0.85 mm	1.4 mm at *x* and 0.9 mm at *y* directions	0.6 mm	0.8 mm	-

* - TT through transmission mode, R – one side access reflection mode, fps – frames per second)

Usually it is declared, that UVS are designed for the diagnosis of the subsurface defects in solids, composite materials and etc. So, in order to get information about defect's size and spatial location UVS must perform measurement operations.

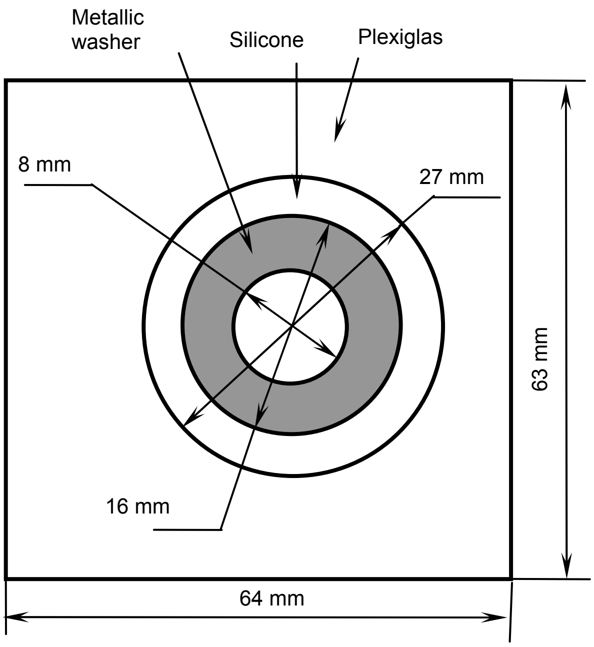


Fig. 1. **The test sample with a washer, embedded in silicone, provided by the manufacturer. The thickness of the test sample is 9 mm**

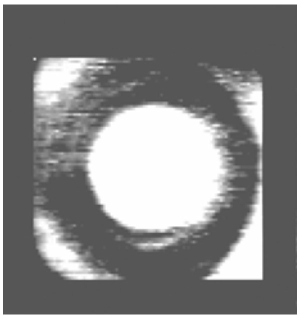


Fig. 2. **The real-time image of the washer sample, embedded in silicon, obtained with UVS Acoustocam I400**

This information has to be presented for the user, who makes a decision about tested object's condition. However, the acoustic images of the test object, obtained with the UVS (Fig. 1-2), usually do not present the quantitative information about defect's size and spatial location. In this case the diagnostic results (or resulting images) of the UVS are not reliable enough for making a decision. Therefore in order to get the impartial and quantitative estimation of the object's testing results, obtained using the UVS, the metrological evaluation of the UVS is required. Such evaluation is value-adding for the acoustic images obtained by UVS. To our knowledge there are no publications about usage of the similar metrological evaluation procedures for UVS, which would give an independent estimation of specified parameters of UVS. So, the objectives of this work are the proposition of the characteristics for metrological UVS evaluation and the investigation of the most suitable methods for their determination.

The tasks of the metrological UVS evaluation

Most of UVS due to their construction properties may be rather easily disassembled into separate units. This gives an unique possibility to evaluate these units of the UVS separately. So, the metrological evaluation of UVS (Fig. 3) may be separated into two tasks.

The first task is the partial evaluation of the UVS. That means the disassembling of the UVS and evaluation of the main parts separately.

The second task is the evaluation of the results, obtained by the UVS.

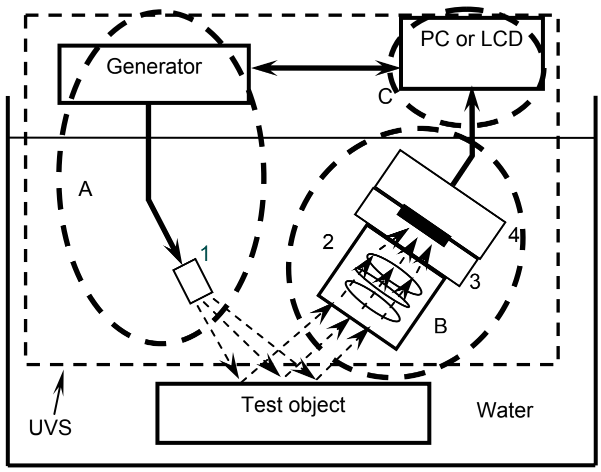


Fig. 3. **The simplified structure of the UVS: A – excitation part, where 1 is the source of ultrasonic waves; B – receiving part, where 2 is the system of acoustic lenses, 3 is the ultrasound sensitive array, 4 is the signal processing equipment; C – is the unit of acoustic image presentation**

It is proposed, that the evaluation of separate parts of the UVS involves the estimation of the signals in the excitation and receiving parts and the estimation of the operation of acoustic lenses system. It has to be defined what signals actually must be generated by an UVS during operation. The mismatch of the declared and measured signals would give an indication about incorrect operation of the UVS. The estimation of the acoustic lenses system operation gives information about performances, e.g. are there distortions of the real object figure in the acoustic image. Also, in order to estimate the functionality of the UVS the evaluation of the dynamic range of the UVS is necessary.

Operation of the whole UVS may be estimated using test objects with a known geometry and dimensions. If the performance of the whole UVS is known, then the evaluation of the results, obtained by the UVS, gives more valuable information about the condition of the real object; e.g the user's decision about the object's condition is legitimated.

The investigation of the acoustic lenses system of the UVS

The excitation signals and radiated by the source signals are proposed to be the first indicators of the right operation of the UVS. The parameters like operating frequency or spatial resolution of the UVS may be obtained from these signals. Usually it is not declared by manufacturers, what are the "right" signals, so the evaluation of the measured signals (Fig. 4-5) comparing their parameters with "right" signals is not performed at the moment.

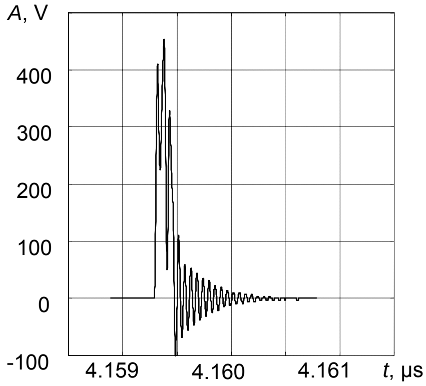


Fig. 4. **The maximum amplitude's excitation signal of the UVS Acoustocam I400**

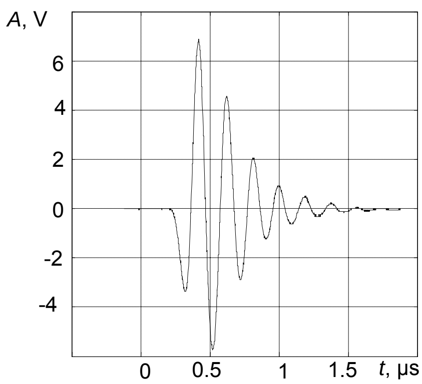


Fig. 5. **The radiated pulse of the UVS Acoustocam I400 transducer, when the excitation signal is as presented in Fig.4. The distance between transmitter and receiver was 10 mm. The receiver was plane 5 MHz, 12 mm diameter transducer**.

The investigation of the acoustic lenses system operation is the important step of the metrological evaluation of the UVS, because the acoustic image of a test object directly depends on a proper operation of the lenses. The investigation was performed using the estimation of the point spread function (PSF) of the acoustic lenses.

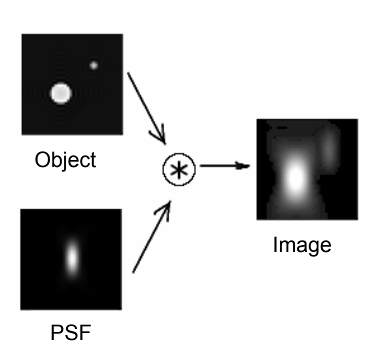


Fig. 6. **The principle of the image formation in visualisation systems. *– denotes convolution.The resulting image of the object depends on PSF [10]**

Actually, the PSF describes visualization system's reaction to the point reflector and is used to estimate the system's spatial resolution (Fig. 6). In a metrological evaluation of the UVS it is necessary to determine the PSF of the acoustic lenses system at different field points, because the different PSF will give a distorted image of the object.

The measurement scheme, presented in Fig. 7, was used for investigation of the PSF of the acoustic lenses system (Fig. 8).

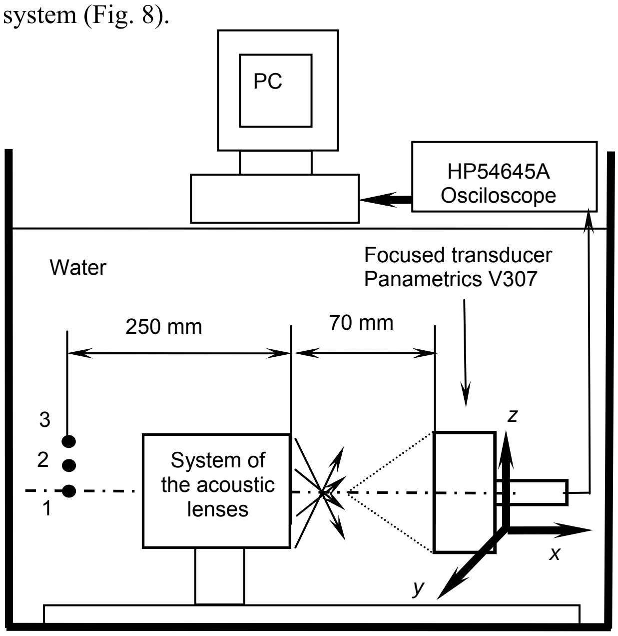


Fig. 7. **The scheme for the investigation of the acoustic lenses system's PSF. 1, 2, 3 are the positions of the metallic ball, the diameter of which is 9.5 mm**

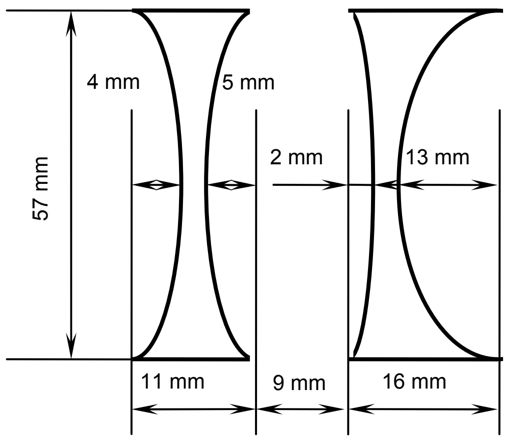


Fig. 8. **The system of the acoustic lenses of the UVS**

The ball was irradiated by a wide ultrasonic beam. The reflector was positioned at different places (Fig. 7) in order to get the reflections, transmitted through the different places of the acoustic lenses. In such a way the PSF in different parts of the acoustic lenses may be estimated. The focused transducer was used to scan the image [11, 12] of the ball, formed by acoustic lenses. The images of the measurement results are presented in Fig. 9 - 11. The images are presented in a black and white scale. The black zone in the centre of the images presents the maximum amplitude reflections from the ball's surface. The axial dimensions y and z of that zone varies by ±0.05 mm at different positions of the ball (Fig. 7). From the results presented follows that the PSF at different field positions is almost the same what indicates a good performance of the investigated acoustic lens system.

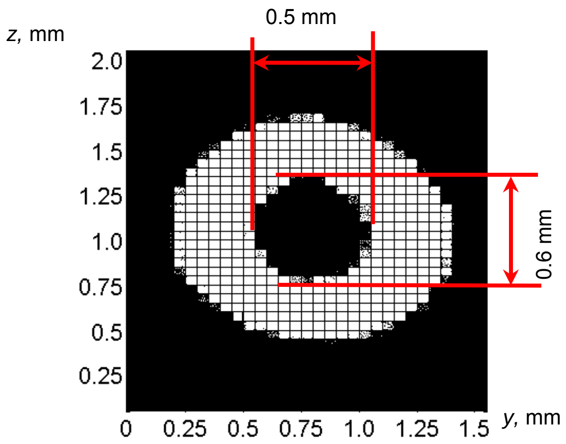


Fig. 9. **The image of the reflection from the metallic ball, formed by acoustic lenses system. The ball's position is 1 (Fig. 7)**

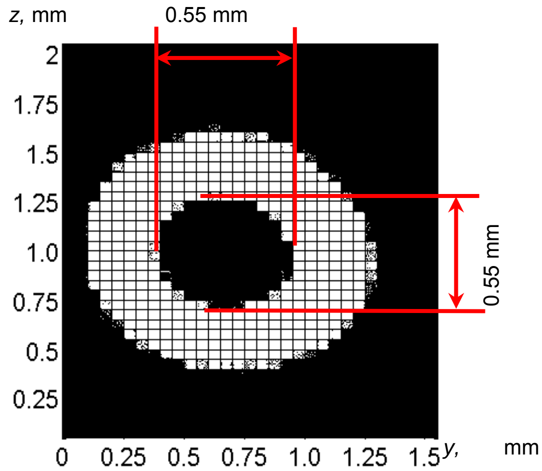


Fig. 10. **The image of the reflection from the metallic ball, formed by acoustic lenses system. The ball's position is 2 (Fig. 7)**

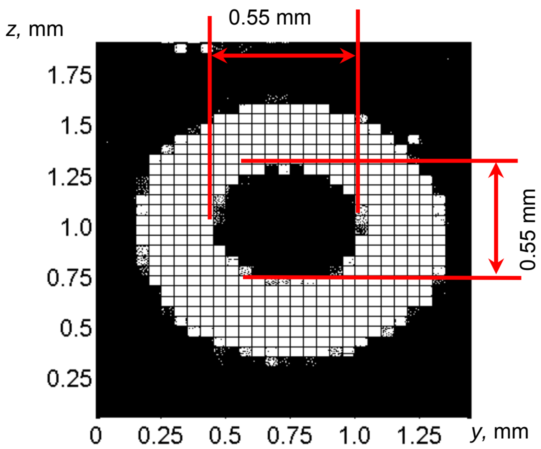


Fig. 11. **The image of the reflection from the metallic ball, formed by acoustic lenses system. The ball's position is 3 (Fig. 7)**

Another way for the lenses investigation is based on the measurements of the test objects with a known in advance geometry. At first the acoustic image of the test object – metallic ring is scanned directly with the focused transducer the frequency of which is rather close to the operation frequency of the UVS. The metallic rings (Fig. 12) are placed on the surface of the plane ultrasonic transmitter and the scanning of the emitted ultrasonic field is provided using a focused receiver (Fig. 13). The obtained images are presented in Fig. 14. It is true to say that the acoustic images of the test objects due to the focusing of the ultrasonic fields do not represent the real dimensions of the objects. But the measurement results (Fig. 14) show, that the width of the rings is the same at various locations. That proves the right operation of the scanning of the test object with a focused transducer.

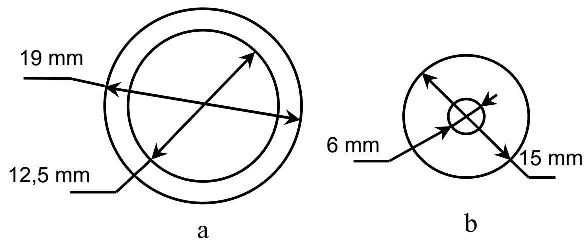


Fig. 12. **The metallic rings, placed on the surface of the transmitter. The thickness of the a ring is 1 mm, the thickness of the b ring is 4 mm**

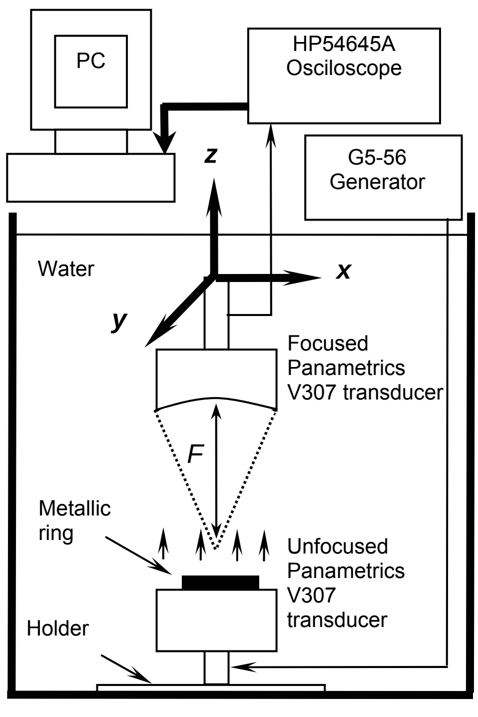


Fig. 13. **The experimental set-up for the scanning of the ultrasonic field, emitted by the plane transmitter with placed on metallic ring measurements of the planar transducer (*F* – focus length of the focused transducer)**

During the second step the system of the acoustic lenses is placed between the transmitter and the focused receiver, similarly to the scheme, presented in Fig. 7. In this case the acoustic images of the rings on the transmitter were formed by acoustic lenses. The formed images were scanned with the focused transducer. The obtained results are presented in Fig. 15.

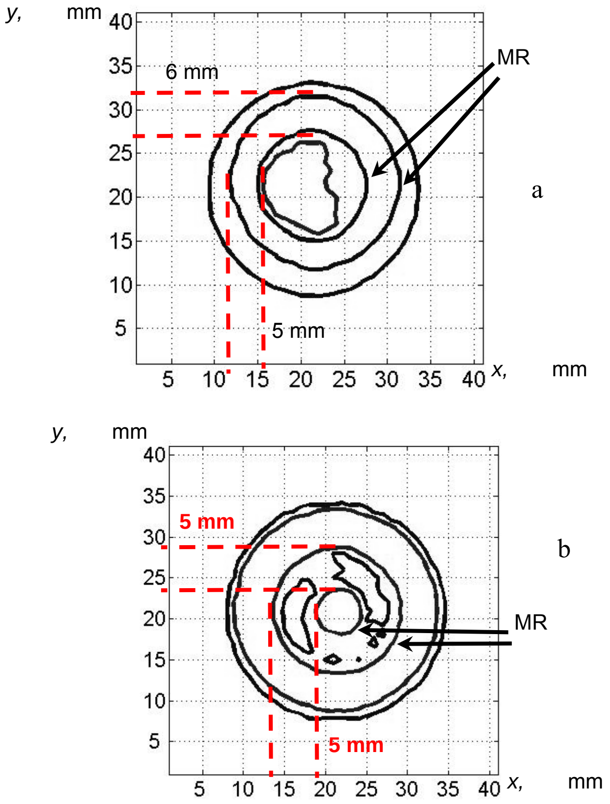


Fig. 14. **The acoustic images of the metallic rings (MR) a and b (Fig. 12), placed on the surface of the transmitter**

The images (Fig. 14-15) are processed using the MatLAB CONTOUR function.

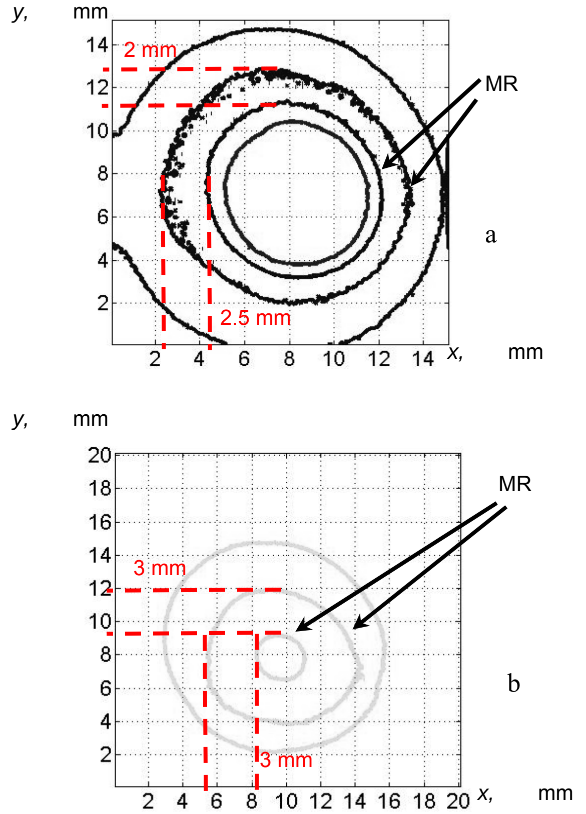


Fig. 15. **The contoured acoustic images of the metallic rings (MR) a and b (Fig. 12), formed by acoustic lenses system. MR – the contours of the acoustic images of the ring**

The results also show (Fig. 15) that the acoustic images of the metallic rings do not match the real dimensions of the rings (Fig. 12) as it was mentioned above. This mismatch is not analyzed in detail, because the purpose of these experiments is to check the functionality of the acoustic lenses system. The results show, that the width of the rings is almost the same in various locations, except the wider zone of the ring in Fig. 15a. This is due to the non-parallel location of the transmitter with ring and the system of the lenses. The results confirm the correct operation of the acoustic lenses system.

The investigation of the dynamic range of the UVS

The dynamic range is an important characteristic of an UVS. The dynamic range determines the interval of the detectable by UVS signals' amplitudes. In most cases the reflected signals from the surface of the object have much more higher amplitude than the signals from the subsurface defects. So, the dynamic range of the UVS has to be large enough for detection of the signals from the subsurface defects. Actually, the conversion of signals in UVS (conversion of electrical excitation signals to acoustical (A unit in Fig. 3), conversion of acoustical signals to electrical (B and C units in Fig. 3)) also influence the dynamic range and in most cases these conversions decrease the dynamic range.

The dynamic range of the signals from the test object was investigated in order to find out the necessary dynamic range for most typical applications of UVS. It is true to say, that the mismatch between the real signals' dynamic range and dynamic range of the UVS equipment, which forms the acoustic images, will cause the distortions in the acoustic image of a real object, some signals may be lost, etc. Actually, the UVS should contain possibility to provide some operating procedures in order to adjust its dynamic range to the dynamic range of the real signals.

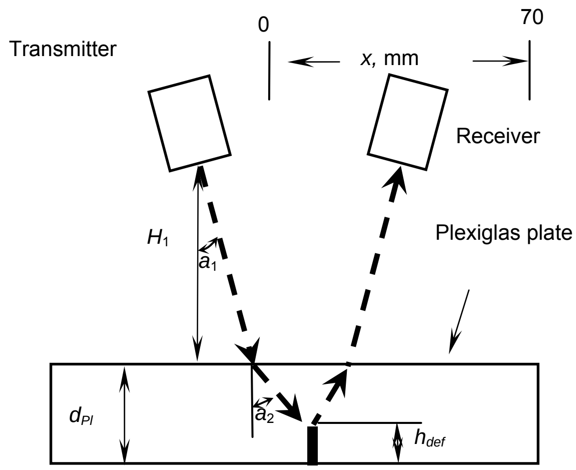


Fig. 16. **The experimental setup for dynamic range investigation of the real signals from the Plexiglas plate**

The experimental setup is presented in Fig. 16. The Plexiglas plate with an artificial crack was chosen for the experiment, because it may be *a priori* said, that the dynamic range of the signals obtained from the Plexiglas plate is the smallest dynamic range required for the UVS.

The wider dynamic range will be required for composite materials, like GLARE, honeycomb, CFRP, etc. The measurement results are presented in Fig. 17.

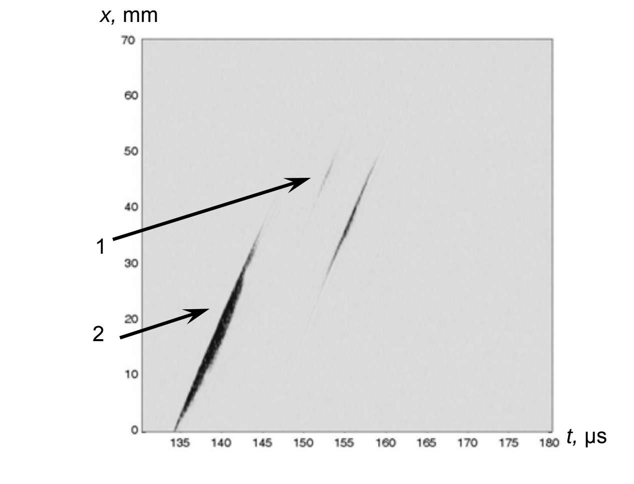


Fig. 17. **The B-scan of the signals from the Plexiglas plate (Fig. 19). 1 – the reflection from the surface of the plate, 2 – the reflection from the artificial crack**

The measured dynamic range of the signals, reflected from the surface of the Plexiglas plate and the artificial crack in the plate is more than 30 dB.

It is declared, the dynamic range of the UVS images is 48 dB. The investigation of the dynamic range of the UVS image was performed. The electrical signals A_{max} and A_{min} of the frame of the UVS image were measured in selected areas (Fig. 18, dashed lines), and the dynamic range of the amplitudes of the signals was calculated according to.

$$D = 20 \cdot \log_{10} \frac{A_{\max}}{A_{\min}} \tag{1}$$

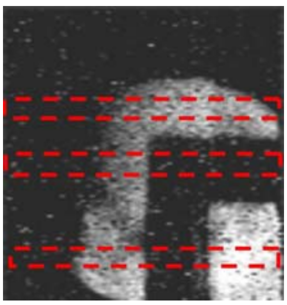


Fig. 18. **The acoustic image, containing signals which were used to determine the dynamic range of the image**

The measurements proved that the dynamic range of the acoustic image of the UVS, obtained in the proposed way is only 25 dB.

The investigation of the images, obtained with UVS

The images obtained with the UVS (Fig. 2, 18, 22) do not give quantitative information about the objects under investigation. However, the images, obtained with a focused transducer (Fig. 21-22), contain a grid, which helps to determine the geometrical parameters of the acoustic image. The knowledge of the geometrical dimensions of the real object and the geometrical dimensions of the object in the acoustic image, obtained with a focused transducer, helps to estimate how many times the dimensions of the real object are decreased (or increased) in the acoustic image. That gives the quantitative information about the object under investigation with unknown geometrical parameters. For this purpose the test sample is a holed aluminium plate was used (Fig. 19). The acoustic images of the sample were obtained with the UVS and also using scanning with a focused transducer. The results are presented in Fig. 21-22. The images, obtained with the UVS (Fig. 20), are noisy and give no quantative data about the geometry of the holes in the sample. These images only show, that “there is something in the object”. For measurements the grid on these images is required, similarly to the images, obtained with a focused transducer (Fig. 21-22).

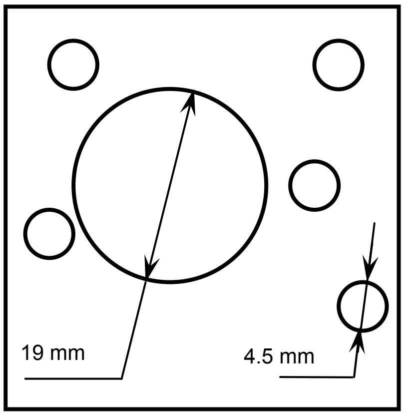
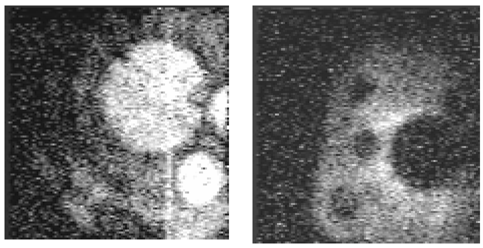


Fig. 19. **The with holes alloy specimen. The thickness of the specimen is 1 mm**



a b

Fig. 20. **The acoustic images of the specimen (Fig. 21), obtained with UVS: a – through transmission mode, b – reflection mode**

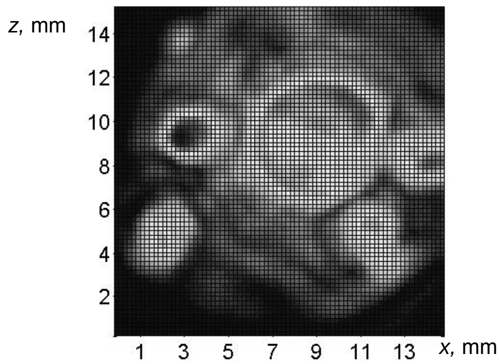


Fig. 21. **The acoustic image of the specimen (Fig. 21), formed by acoustic lenses and obtained using a focused transducer in the through transmission mode**

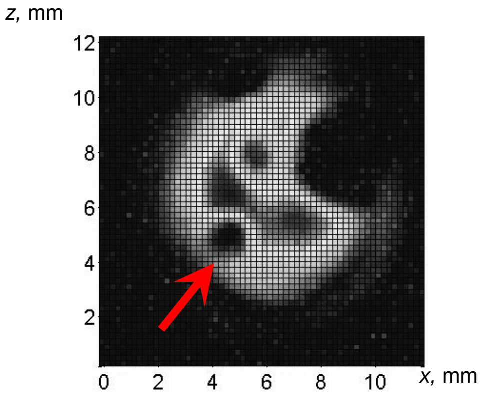


Fig. 22. **The acoustic image of the specimen (Fig. 21), formed by acoustic lenses and obtained using a focused transducer in the reflection mode**

For example, the diameter of the image of the hole, marked with the arrow in Fig. 22 is 1.4 mm. The diameter of the real hole in the sample is 4.5 mm. So, the image of the hole has decreased approximately 3 times. Declaring, that the scanning with the focused transducer was provided to imitate the receiving array of the UVS, the image of the real object, obtained with the UVS, will be also reduced 3 times.

Conclusions

The main steps for metrological evaluation of UVS is proposed. The object's test results, obtained with the UVS, can be estimated impartially and quantitatively using the proposed approach. The tasks for the metrological evaluation of the UVS are formulated and the characteristics for the metrological UVS evaluation are proposed. The instrumentalities for determination of the most significant UVS characteristics are investigated. The results show suitability of the proposed techniques for metrological evaluation of the UVS. The proposed principles of metrological evaluation may be useful for building the methodology of the calibration of UVS.

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Realiuoju laiku veikiančių neardomiesiems tyrimams skirtų ultragarsinių vizualizacinių sistemų (UVS) patikros metodikos principai

Reziumė

Gamintojų deklaruojama, kad neardomiesiems tyrimams skirtos realiuoju laiku veikiančios ultragarsinės vizualizacinės sistemos (UVS) yra diagnostinės, tinkančios popaviršiniams defektams aptikti kietosiose medžiagose. Taigi iš principo jos turėtų atlikti matavimo procedūrą ir vartotojui pateikti informaciją apie popaviršinių defektų matmenis ir padėtį erdvėje. Tačiau su tokia įranga gauti tiriamųjų objektų akustiniai laukų paveikslai nepateikia informacijos apie matomų popaviršinių defektų matmenis ir padėtį erdvėje. Tokiu atveju, priimant sprendimą dėl tiriamojo objekto tinkamumo toliau eksploatuoti, remtis UVS rezultatais nepatikima. Todėl iškilo poreikis atlikti UVS metrologinį įvertinimą, nes iki šiol nėra paskelbta apie panašių įvertinimų metodikų taikymą. Realiuoju laiku veikiančių neardomiesiems tyrimams skirtų UVS metrologinio įvertinimo metodikos principai buvo kuriami neturint panašių atvejų patirties. Šiame darbe suformuluoti UVS patikros uždaviniai, pasiūlytos UVS metrologiškai apibūdinančios charakteristikos. Pasiūlyti ir ištirti charakteristikų nustatymo būdai, pateiktas siūlomos metodikos operacijų rinkinys. Taikant pasiūlytus UVS patikros principus, gaunamas objektyvus kiekybinis objektų tyrimo rezultatų įvertinimas ir kartu padidinama šių rezultatų praktinė reikšmė.

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