# INVESTIGATION OF RELATIVE SENSITIVITY X-RAY TELEVISION SYSTEMS ON THE BASIS OF HIGH-SENSITIVITY CCD-CAMERAS AND X-RAY MONOCRYSTAL SCREENS

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X-ray TV systems (XRTS), unlike the radiography, allow the objects to be controlled both in statics and dynamics more economically. The systems with transformation of shadow X-ray image into optical one using fluorescent screens or X-ray image intensifiers (XRII) are widely spread. The screens are more advantageous than XRII: possibility to change the size of working area; simple design; low cost and other. The development of such XRTS was delayed by a low luminescence intensity of screens. Relatively not long ago the highly-sensitive light-signal transducers in the form of arrays with charge coupling (CCD-arrays) and possibility to use them in XRTS appeared. CCD-arrays are more preferable as compared to transmitting electron beam tubes owing to compactness, absence of lag effect and longer life. During recent years the series of CCD-arrays has been developed where sensitivity is commeasurable with sensitivity of highly-sensitive transmitting tubes of the isocon and supervidicon type. The TV systems based on CCD-arrays are effectively applied in non-destructive testing of moving objects, providing the relative sensitivity of control of 1.7 – 2.5 % within the wide range of steel thicknesses [1].

The further increase in relative sensitivity of control is possible due to transfer of CCD-arrays into the mode of controllable duration of images accumulation. After termination of accumulation the image is read from the array per one picture and memorized in the memory device, from which it is displayed on the monitor, into the computer for processing and archiving. Therefore, actual is the ability to calculate and study such systems in the mode of controllable duration of image accumulation.

Let us calculate the possibilities of definite XRTS developed for a laboratory of the E.O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine (NASU). Here, the CsI(TI) monocrystal screen of 200 mm diameter, the array EXviev HAD CCD of the company Sony of type ICX429ALL of the format ½'' (diagonal size is 8mm) with the amount of active light-sensitive [2] elements 752 x 582 are used. The camera has a feasibility to operate both in broadcast standard of image decomposition (625 lines, 25 pictures per sec, interlacing), as well as in the mode of controllable duration of image accumulation on CCD-array (continuity of accumulation is up to 2048 pictures, the duration of a picture is 40ms). The camera is equipped with the auto-zoom lens Computar T4Z2813 with a relative hole 1:1.3 and focal distance of 2.8-12 mm. To transfer the image from the X-ray screen to the input of TV camera the angular optic attachment with a mirror is used.

The image of an object being inspected is observed on the 17-inch monitor of the HITRON HM1723C type. To enter the images into computer the high-speed input unit through interface USB 2.0 is used providing the possibility of monitoring and recording of images in the computer in real time (the pictures frequency is 50Hz, picture size is 720 x 576). There is also a possibility to record single image pictures with high resolution in the size of 1440 x 1152 into the computer. The control of all modes of TV camera (duration of accumulation on the CCD-array, video path gain, black level and other) is performed from the computer through the interface RS-232.

The mentioned XRTS operates in the set with X-ray device "EXTRAVOLT-350" of CJSC "TESTRON" production (St.-Petersburg, Russia) with a two-focus metal-ceramic X-ray tube MB 350 of Tales Electron Devices company (France). The steel plates of 10, 20 and 30 mm thickness were used for the control. The measurement of relative sensitivity was performed using groove (Fe-1, Fe-2) and wire (Fe-2 and Fe-3) penetrameters of sensitivity. The steel plates with penetrameters of sensitivity were placed in close vicinity to the screen. The distance between the anode of X-ray tube and the screen was 350 mm.

The relative sensitivity is determined for the case of use of a wire penetrameter according to the formula: $K_d = (d/H_{kz})\times 100$, where d is the smallest diameter of revealed wire, $H_{kz}$ is the thickness of object being inspected.

The flaw can be detected with some probability if its luminance difference $k_B$ exceeds or equal to the threshold contrast $k_{por}$. Therefore, to determine the minimal size of flaw, which can be detected, it is necessary to plot the dependencies of luminance and threshold contrast on the size of flaw and to find their point of intersection.

To determine $k_B$ and $k_{por}$ the following formulae were used:

$$k_B = K_S M(\nu), \tag{1}$$

$$k_{por} = \sqrt{\frac{\Psi_{por}^2}{(T_i / T_{EX})(\Omega / A_{CCD})} M^2(\nu) K_N^2 + k_\nu^2}\ , \tag{2}$$

where $K_s$ is the charge image contrast; M(v) is SFC of XRTS; v is the spatial frequency, which corresponds to cross sizes of flaw; $\Psi_{por}$ is the threshold signal/noise ratio; $T_i$ is the time of integration using visual analyzer; $T_{EX}$ is the duration of picture accumulation. $\Omega$ is the area of flaw reduced to the surface of CCD-array, $A_{CCD}$ is the area of light-sensitive element of CCD-array, $K_N$ is the relative average fluctuation in calculation per area of supersensitive element of CCD-array during the time of accumulation; $k_v$ is the threshold contrast of visual analyzer.

Usually [1], the spatial-frequency characteristic (SFC) M(v) is taken to be equal to unity, i.e. the influence of SFC was not accounted. Let us consider and determine SFC M(v) which is equal to the product of SFC scheme of formation of shadow X-ray ima ge of the object $M_P(v)$, SFC of X-ray screen $M_{CsI}(v)$ and SFC of CCD-array $M_{CCD}(v)$.

To find SFC of the scheme of formation of X-ray image the following formula was used [3]:

$$M_p(\nu) = \exp(-\pi^2 \nu^2 R_T^2), \tag{3}$$

where $R_T = \frac{\sqrt{2} f \beta_0}{6}$ is the effective radius of X-ray image of spot flaw equal to the distance from the centre of image to the point where the intensity of radiation is decreased by $e$ times; $f$ is the size of focus of X-ray tube (in our case $f$ = 3.5 mm); $\beta_0 = \frac{D}{F - D}$ is the ratio of increase of focus of X-ray tube; D is the distance between the object and X-ray monocrystalline screen which was taken equal to the thickness of the object being inspected; F is the distance between the focus of X-ray tube and X-ray monocrystalline screen (F=35 cm).

SFC of CCD-array is determined as follows [4]

$$M_{CCD}(1/n_L) = \{(2n_L / \pi)\sin[\pi /(2n_L)]\}^2 \sqrt{\alpha_1^2 + \beta_1^2 / n_L}\ , \tag{4}$$

where $\alpha_1$ and $\beta_1$ are calculated according to the formulae:

$$\alpha_1 = \sum_{m=1}^{2n_L} \cos\{\pi[(2m-1)/(2n_L) + \Delta_0 / L_y]\}\cos[\pi(2m-1)/(2n_L)];$$

$$\beta_1 = \sum_{m=1}^{2n_L} \cos\{\pi[(2m-1)/(2n_L) + \Delta_0 / L_y]\}\sin[\pi(2m-1)/(2n_L)],$$

where $n_L$ is the amount of elementary cells of CCD-array which find place at the semi-period $L_y$ of input light signal; $m$ is the number of elementary cell; $\Delta_0$ is initial phase shift of input signal (in our calculations it is taken equal to zero, as we consider the worst possible case). Here, to obtain the SFC for the definite CCD-array the argument of function $M_{CCD}$ should be multiplied by $L_{py}\delta$ ($\delta$ is the coefficient of decrease of optic system, which is equal to $\delta$ = 30.4 in our case).

The SFC of X-ray monocrystalline screen of material CsI(TI) $M_{CSI}$(v) is taken from [5] and interpolated by cubic splines.

The mentioned components of SFC, calculated for the conditions of experiments conducted by us, and also resulting SFC of XRTS $M(\nu) = M_p(\nu) M_{CCD}(L_{py}\delta\nu) M_{CsI}(\nu)$ are given in the Figure 1.

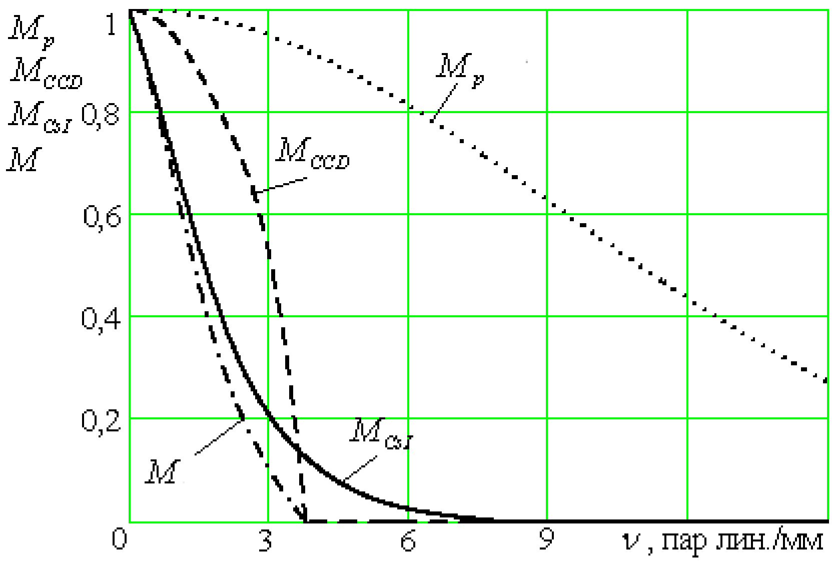


Fig. 1 SFC of the scheme of formation of X-ray image $M_p$(v) at D = 10 mm, CCD-arrays $M_{CCD}$(v), X-ray monocrystalline screen of the material CsI(TI) $M_{CSI}$(v) and resulting SFC of XRTS M(v).

To calculate $K_S$ and $K_N$ used in formulae (1) and (2) the mathematic model of transformation of signals in the XRTS based on X-ray screen and CCD-array is taken, which is described in detail in [1]. The model considers the process of formation of shadow X-ray image of object being inspected, physical principles of functioning of scintillation transducers of radiation and devices with charge coupling. On the basis of formed model in such a way one can determine the amount of electrons, accumulated in a cell of CCD-array of electrons, which corresponds to a difference signal from the flaw in X-raying object $Q_S / q$ (valid signal) and amount of accumulated electrons corresponding to the background signal (signal from the flaw-free area) $Q_\phi / q$. Then $K_S$ and $K_N$ are determined according to the formulae:

$$K_S = \frac{Q_S / q}{Q_\Phi / q}, \tag{5}$$

$$K_N = \frac{1}{\sqrt{Q_\Phi / q}}. \tag{6}$$

Other values, included into formula (2), were determined in the following way. The area of flaw, reduced to the surface of CCD-array, is $\Omega = d^2 / \delta^2$, where $d$ is the diameter of wire penetrameter. The area of light-sensitive element of CCD-array ICX-429ALL is $A_{CCD} = L_{py} \times L_{pz} = 8{,}6 \times 8{,}3$ μm². The duration of one accumulation picture is $T_i$ = 40 ms. The time of integration time by visual analyzer is $T_i$

= 0.1 sec, threshold contrast is $k_v$=2 %, threshold signal/noise ratio is $\Psi_{por}$ = 3 [6, 7]. In accordance with [6] for the wire of wire penetrameter the spatial frequency is: $\nu = \frac{1}{2{,}5d}$.

**The results of theoretical and experimental investigations.** The Figure 2 shows diagrams of dependencies of contrast of output signal of CCD-camera and threshold contrast upon the size of flaw (diameter of wire penetrameter), calculated using the described method. As is seen from the Figure, the contrast of output signal of CCD-camera grows practically linearly with increase in a flaw size (wire diameter). The inclination angle $k_B$ is the smaller the larger is the thickness of specimen being inspected and the higher is the voltage at the anode of the tube. The value of threshold contrast $k_{por}$ is as higher as smaller is the total amount of quanta created by the image. Thus, it is seen that $k_{por}$ decreases with the increase in amount of accumulation pictures. The observed regularities of characteristics of the Figure 2 are correlated with the known principles of formation of X-ray image [3].

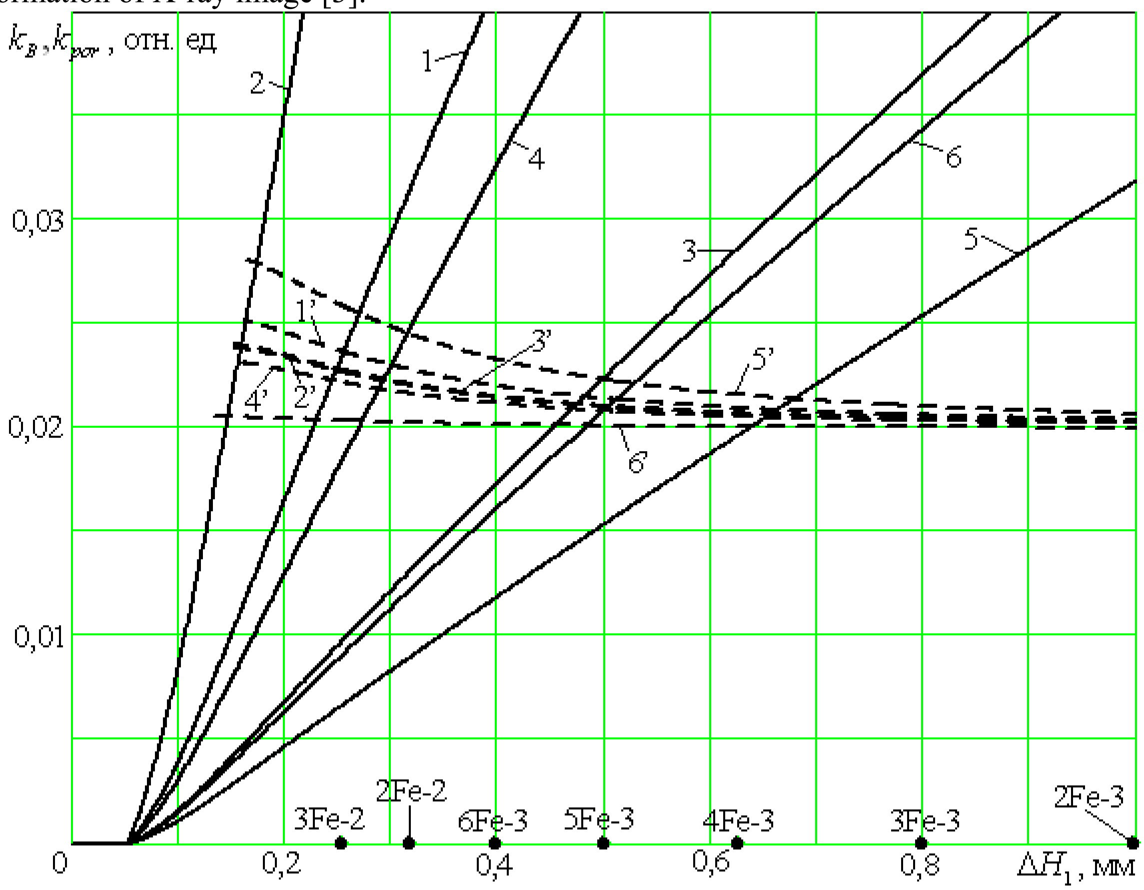


Fig. 2. Dependencies of contrast of output signal of CCD-camera $k_B$ (solid lines) and threshold contrast $k_{por}$ (dotted lines) on the size of flaw $\Delta H_1$ for wire penetrameters Fe – 2 and Fe – 3.
Curve 1 – $k_B$ at $H_{kz.}$ = 10 mm, $U_A$ = 160 kV, $I_A$ = 10 mA, $N_k$ = 1; curve 2 – $k_B$ at $H_{kz}$ = 10 mm, $U_A$ = 100 kV, $I_A$ = 8mA, $N_k$ = 64; curve 3 – $k_B$ at $H_{kz}$ = 20 mm, $U_A$ = 240 kV, $I_A$ = 8 mA, $N_k$ = 1; curve 4 – $k_B$ at $H_{kz}$ = 20 mm, $U_A$ = 140 kV, $I_A$ = 10 mA, $N_k$ = 32; curve 5 – $k_B$ at $H_{kz}$ = 30 mm, $U_A$ = 260 kV, $I_A$ = 8 mA, $N_k$ = 1; curve 6 – $k_B$ at $H_{kz}$ = 30 mm, $U_A$ = 200 kV, $I_A$ = 10 mA, $N_k$ = 64.

In Figure 2 the characteristics, the number of which is marked by a dot mark, denote the appropriate $k_{por.}$

The minimum size of flaw which can be detected by XRTS at the mentioned definite parameters of operation mode is defined by the point of intersection $k_B$ and $k_{por}$ corresponding to it. The calculated value of relative sensitivity of XRTS was defined by the smallest diameter of wire penetrameter for which the criterion $k_B \geq k_{por}$ is realized (the nearest value of diameter of penetrameter on the side of large sizes relative to point of intersection of appropriate curves in Figure 2).

The Table gives the results of experimental investigations of relative sensitivity of XRTS at the control of specimens of different thickness $H_{kz}$ for different modes of system operation (anode voltage $U_A$ and anode current of X-ray tube $I_A$, number of accumulation pictures of CCD-camera $N_k$). The amount of accumulation pictures $N_k$ = 1 corresponds to the broadcast standard of image decomposition. The results of measurement of relative sensitivity of the control are presented by the numbers of the smallest groove detected by depth and smallest wire detected by diameter with the designation of types of appropriate penetrameters of sensitivity (Fe-1, Fe-2 or Fe-3). The Table gives also the values of sensitivity of control using the groove ($K_k$) and wire ($K_d$) penetrameters. In the last column of the Table the values of relative sensitivity of XRTS calculated using offered methods are given for the wire penetrameters.

Table. The experimental and calculated values of relative sensitivity of XRTS

| № | $U_A$, kV | $I_A$, mA | $H_{kz}$, mm | $N_k$ | Groove penetrameter | | Wire penetrameter | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | № groove and type of the penetrameter | $K_k$, % | № wire and type of the penetrameter | $K_d$, % | $K_d$, %, calc. |
| 1 | 150 | 10 | 10 | 1 | 5 Fe-1 | 1.67 | 2 Fe-2 | 3.2 | - |
| 2 | 150 | 10 | 10 | 16 | 5 Fe-1 | 1.67 | 3 Fe-2 | 2.5 | - |
| 3 | 160 | 10 | 10 | 1 | 5 Fe-1 | 1.67 | 3 Fe-2 | 2.5 | 2.5 |
| 4 | 100 | 10 | 10 | 1 | - | - | - | - | - |
| 5 | 100 | 10 | 10 | 64 | 5 Fe-1 | 1.67 | 3 Fe-2 | 2.5 | 2.5 |
| 6 | 200 | 10 | 20 | 1 | 6 Fe-2<br>2 Fe-1 | 2.1<br>2.27 | 4 Fe-3 | 3.15 | - |
| 7 | 240 | 8 | 20 | 1 | 6 Fe-2<br>3 Fe-1 | 2.1<br>1.8 | 4 Fe-3 | 3.15 | 2.5 |
| 8 | 240 | 8 | 20 | 16 | 4 Fe-1 | 1.36 | 5 Fe-3 | 2.5 | - |
| 9 | 140 | 10 | 20 | 32 | 3 Fe-1 | 1.8 | 5 Fe-3 | 2.5 | 1.6 |
| 10 | 260 | 8 | 30 | 1 | 6 Fe-2 | 1.47 | 3 Fe-3 | 2.67 | 2.67 |
| 11 | 300 | 6 | 30 | 1 | 6 Fe-2 | 1.47 | 3 Fe-3 | 2.67 | - |
| 12 | 300 | 6 | 30 | 16 | 6 Fe-2<br>2 Fe-1 | 1.47<br>1.56 | 4 Fe-3 | 2.1 | - |
| 13 | 200 | 10 | 30 | 64 | 3 Fe-1 | 1.25 | 5 Fe-3 | 1.67 | 1.67 |

As is seen from the Table during the operation of CCD-camera in broadcast standard of image decomposition ($N_k$ =1) the relative sensitivity for thickness $H_{kz}$ = 10mm is $K_k$ =1.67 % and $K_d$=2.5 % at $U_A$ = 160 kV. With decrease in anode voltage down to $U_A$ = 100 kV the grooves and wires stop being detected. However the accumulation on the CCD-array of $N_k$ = 64 pictures provides the same sensitivity as at $U_A$=160 kV (item 5 of the Table). The images obtained after accumulation are more qualitative due to the absence of noises on them. The Figure 3 gives the image of welded joint obtained after accumulation in CCD-camera of $N_k$ = 64 (the modes correspond to item 5 of the Table).

The best relative sensitivity of the control for the thickness of steel $H_{kz}$ =20 mm achieved in broadcast standard of decomposition was $K_k$ =1.8 % and $K_d$=3.15 % at $U_A$ = 240 kV (according to item 7 of the Table). The accumulation $N_k$ =16 at the same anode voltage improves sensitivity of control $K_k$ from 1.8 % to 1.36 % and $K_d$ from 3.15 % to 2.5 %. The decrease in anode voltage down to $U_A$ = 140 kV in broadcast standard of decomposition results in sharp deterioration of sensitivity (the grooves and wires of penetrameters are almost not detected). However the accumulation on the CCD-array of $N_k$ = 32 pictures provides the same sensitivity $K_k$ as at $U_A$=240 kV and also improves the control sensitivity $K_d$ to 2.5 % as compared with $U_A$=240 kV . The appropriate image of welded joint is given in the Figure 4 (item 9 of the Table).

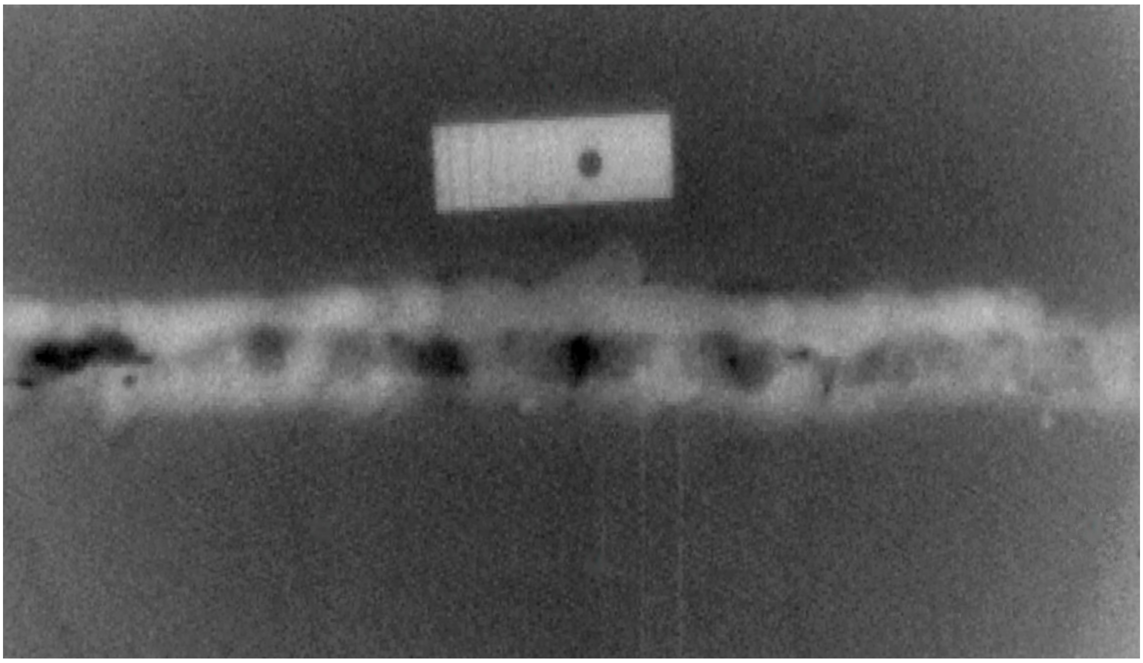

Fig. 3 Image of welded joint (modes correspond to item 5 of the Table)

The similar regularity is also observed for the thickness $H_{kz}$ =30mm. The sensitivity of control achieved in broadcast standard of decomposition was $K_k$ =1.47 % and $K_d$ = 2.67 % at $U_A$ = 260 kV. The accumulation on the CCD-array of $N_k$ =16 pictures improves the sensitivity $K_d$ from 2.67 % to 2.1 %. And at the decrease in anode voltage down to $U_A$ = 200kV the accumulation of $N_k$ = 64 pictures allows achieving the sensitivity of control $K_k$ =1.25 % and $K_d$=1.67 % (item 13 of the Table) that exceeds the sensitivity obtained at anode voltage $U_A$ = 260 kV.

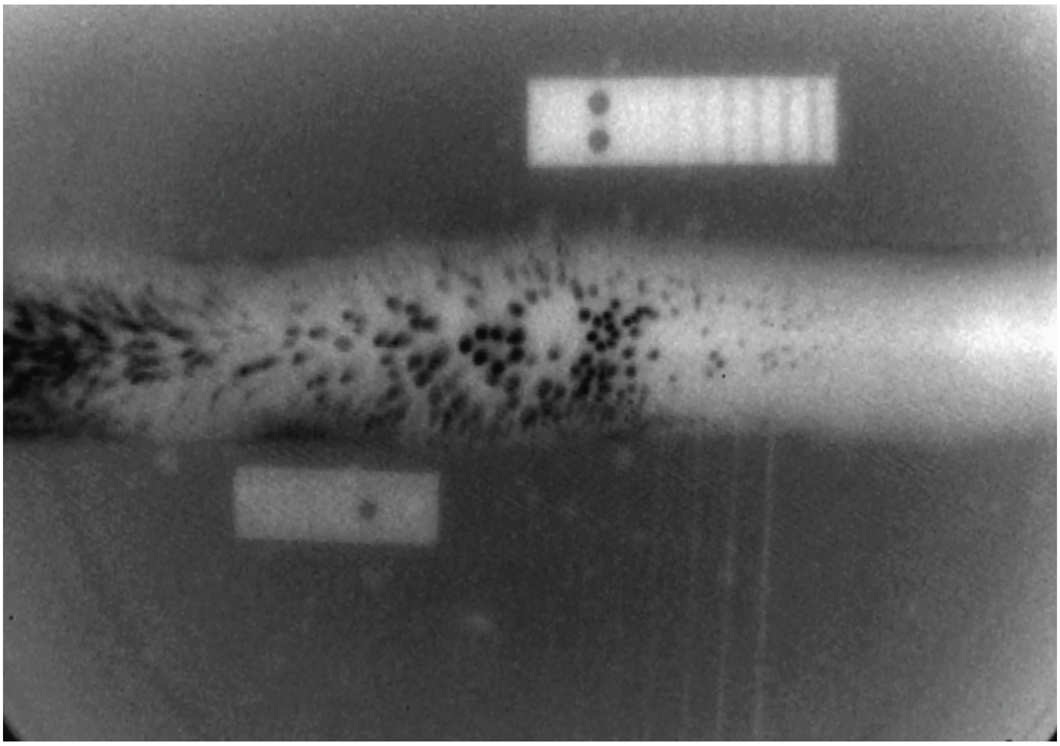

Fig. 4. Image of welded joint (modes correspond to item 9 of the Table)

It is seen from the Table that calculated estimates are well correlated with experimental data due to the fact that spatial filtration was taken into account.

The transition of CCD-cameras of XRTS into the mode of controllable duration of images accumulation allows also the effective application of small-sized pulsed X-ray devices and conduction of control under field conditions and in hard-to-reach places. Thus, for example, during operation of XRTS with a pulsed device MIRA-2D the sensitivity of control of 2.5 % was achieved at X-raying of steel of 10 mm thickness and accumulation of 256 pictures on the CCD-array

The Figures 5, 6 show photos of X-ray TV system manufactured at the E.O.Paton Electric Welding Institute of NASU in collaboration with the Chair of electron instruments and devices of Kiev Polytechnic Institute and high-energy X-ray laboratory where this equipment is used.

**Conclusions**

1. The described methods of calculation of relative sensitivity of X-ray TV systems based on the monolithic crystal CsI(TI) and CCD-array consider the process of formation of a shadow X-ray image of the object being controlled, physical principles of functioning of scintillation transducers and devices with charge coupling, spatial filtration of images. The method evaluate characteristics of such X-ray TV systems with a sufficient accuracy.
2. Transition of CCD-cameras into the mode of controllable duration of images accumulation makes it possible to improve the relative sensitivity of X-ray TV system, to enhance the quality of obtained images due to elimination of noises and to decrease significantly the required capacity of exposure dose of X-ray radiation.
3. The application of the mode of controllable duration of images accumulation in CCD-cameras allows replacing the radiography control in field conditions and hard-to-reach places by using small-sized X-ray devices. The developed system is used at the E.O. Paton Electric Welding Institute of NASU.

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