Structure-oriented algorithms of vizualization of zones of crack formation in welding

Vladimir BARANOV[1], Uwe EWERT[2]

1) INTROSCOPY INSTITUTE BY TOMSK POLITECHNIC UNIVERSITY, Tomsk, Russia
2) BUNDESANSTALT FÜR MATERIAL FORSCHUNG UND – PRÜFUNG , Berlin, Germany

Introduction

Structure-oriented approach was successfully applied to reconstruction of many test-objects in different areas of NDT, in particular, in civil engineering. [10]. As to computerized diagnostics of crack at the stage of formation, it remains to be a difficult problem. even with the use of vigorous techniques. A real crack in welding represents a complex "non-classical" object, extremely inconvenient for visualisation by tomographical methods. Even more, a reconstruction of crack can to serve as pattern of ill-posed problem, in which the "ill-posedness" appears in its utmost and grotesque form. Strictly speaking, tomography of crack is impossible. However, the development of quasitomographic, in essence statistical, methods for description of cracks distribution is realistic In this case in mathematical model includes some special factors should be taken into acoount; among them preferable orientation of microcracks in their spatial distribution.

The questions of mathematical NDT and materiology, in particular questions of visualization of cracks and cracks formation are closely bound. Formation of cracks occurs in "critical" zones where such factors as vibration, gradients of mechanical pressure, of temperatures etc. are intensified. Just due to them the formed cracks have the certain orientation, for example the most damgerous cracks in welding are oriented along the welding. Generally speaking, images of "cracks" on registered X-ray projections before the critical state of test-object are results of accumulation of weak contributions from huge number of microcracks in zone.

The essential parameter which defines the orientation of a single microcrack, it is the angle α between the preferable direction ($\alpha = 0$) and the plane of microcrack. It is assumed, that the unit vector $\boldsymbol{N}$ of this preferable direction is constant in zone. In case a test-object has specifiic shape which is essential for testing (for example, it has curved surfaces as by testing of circumferential welding in tubes) this directional vector is not constant in an ordinary carthesian system of coordinates (although it can be considered as constant in a relatively small "local spot" of zone). With the use of an appropriate transformation the natural "inner geometry" of testing can be reduced to the carthesian geometry in which $\boldsymbol{N} = \boldsymbol{const}$ and curved surfaces are mapped onto planes. It is possible, at least in the ROI – "region of interest" of zone. In consideration of constitutive aspects of crack formation and visualization the carthesian system of coordinates is used There exists some angular distribution $W(\alpha)$ for microcracks in zone, which is likely close to normal, at least in initial stages of crack formation. By radiographic inspection of welding the formed "cracks" (but indeed, some fragments of crack formation zone, maybe even in later stages of its evolution) are visible in a range of angles α up to 10° and more, that allows to estimate the variance of $W(\alpha)$. Due to such dispersion "tomography" become already possible because a set of projections with different angles of view become accessible. But because beam-sums for K beams (with orientation angles α_k, $k = 1, \ldots K$), incidental to their arbitrary common point (x, y, z), represent contributions from independent subsystems of microcracks (these subsystems have no "material intersection" between them), needless to say, that any individualized tomographic visualization of a microcrack is not feasible. In the framework of a statistical quasitomograpic approach it is reasonable to assume, that angular distribution $w(\alpha)$ in a big enough "elementary volume" in zone is close to "common" distribition $W(\alpha)$, in the other words to assume *spatial homogeneity* of $w(\alpha)$, its invariantness with respect to every possible shifts in zone.

In conventional computerized tomography the object of reconstruction is a scalar field of "coefficient of linear attenuation" $\mu = \mu(x, y, z,)$. As to such particular object as crack, the reconstructed field should be represented in form $\mu = \mu(x, y, z, \alpha)$ due to factor of anisotropy. The image under reconstruction is 4-dimensional one and due to above mentioned reasons such 4-dimensional tomographic problem for cracks is unsoluble. Nonetheless, the assumption $w(\alpha) = W(\alpha)$ allows to "equalize" projections in the angle range, where $W(\alpha) \neq 0$ (in the interval of statistical stability of $W(\alpha)$, far from "tails" of the distribution) by division of beam-sums into corresponded values of $W(\alpha)$ and multiplication to unified (for all α) normalizing factor λ. This, in turn, enables to reduce the reconstruction problem to 3-dimensional one – to the reconstruction of some "effective" scalar field $\mu_{eff} = \mu_{eff}(x, y, z)$, which describes the volume distribution of microcracks with different possible orientations in zone of crack formation. (According to the principle of spatial homogeinity of $w(\alpha)$ all the differently oriented subsystems of microcraks become "bounded"). Thus, the beam-sums of the "equalized" projections are integrals of $\mu_{eff}(x, y, z)$ along beams. Because the angular integration of $\mu(x, y, z, \alpha)$ (which is resulted in $\mu_{eff}(x, y, z)$) does not depend on x, y, z, it is also reducible to procedure of "equalization". Roughly speaking, the value $\mu_{eff}\Delta x\Delta y\Delta z$ represents the "number of microcracks" in the volume $\Delta x\Delta y\Delta z$, so that the size of a single microcrack is less than its critical size r_c (corresponded to the state before rapid formation of a macrocrack), whereas the sizes Δx, Δy, Δz of elementary volume are much greater than r_c and comparable to the size of one pixel of projectional image.

Structure-oriented methods for crack detection

Let's consider group-teoretical algorithms of spatial filtration wich are suitable for revealing such objects as a zone of formation of cracks in a welding. Due to preferable orientation the distribution of microcracks which give the contribution to a projectional picture of a zone, represent extended formations. If they do not give any contribution to the local image inside a sliding window the given image within the limits of the statistical significance is pertinent to consider as isotropic. Otherwise there exist significant deviations from isotropy.. A group of local symmetry (or group-theoretical filte) in this case will be the group of rotation (called also group *SO (2)*) of the local microimage around of the central element. This group describes a background, "empty space" without a signal. All points of a zone considered as centres of local images, and satisfying to local isotropy are "equal" among themselves. On the contrary, statistically significant anisotropy testifies occurrence of "a semantic signal » (for example, "defect", we admit a fragment of a crack etc. Thus, "dissymmetry create phenomenon" (P.Curie) Because deviations from norm are less than norm, they briing more semantic information, therefore it is natural to construct the algorithm of recognition in such a manner that symmetry describes "background" and "norm", i.e. the most probable and trivial that can take place. Presence of symmetry is regarded as a zero group-heoretical statistical hypothesis, and occurrence of "defect", as an alternative hypothesis.

Algorithms of .recognition of anisotropy with *SO (2)* as key hypothesis can be constructed by different ways. One of considered by us approach is connected with modification of known in image processing Hough transformation [21] which is mathematically equivalent to Radon transformation [22]. Unfortunately, these techniques are suitable only for visual recognition and qualitative estimation of very much limited class of images. According to the stated by us scheme the transformation of Radon-Hough as the method of image processing of images can be advanced and transformed into normal procedure of a spatial filtration by its application to the local image in a "sliding window". But in this case it should include also the subsequent .synthesis of one-dimensional Radon projections for estimation of "statistics" inside the window. Statistical estimation is an inverse problem. Its solution is not not aimed фе tomographic reconstruction of initial local image, but at effective estimation of parameters of "secondary" semantic elements Isotropic microimages are invariant with respect to Abel transformation, widely used in diagnostics of plasma bunches(beams) [23]. Recognition of anisotropy is reduced, thus, to allocation of not degenerated Radon's objects on a background of degenerated Abel's ones on the basis of analisis of variance

In the other variant of algorithm of recognition of anisotropy (with practically minimal computing expenses) sample statistics are calculated on some subsets of the local image, namely along the direct lines which pass through the central element. . N different fixed directions which are appropriate to N groups of the data for these subsets, were considered.. For definiteness sake, we assume a sliding window square with half-width equal to M. . Let p_{ij} и r_{ij} – brightnesses of elements of initial and final images (i=1, 2,...,I, j=1,2,...,J, where I and J – dimensions of the image), n (n=1, 2, ..., N) – number of an any direction a_{1ij}, a_{2ij}, ..., a_{Nij} – average values and q_{1ij}, q_{2ij}, ..., q_{Nij} – root-mean-square in N groups of data (at calculation of these values the central element was not accounted). In order not to make the formula bulky, indexes i and j will be further omitted. We shall consider parameter n as the factor presumably influencing average values a_1, a_2, ..., a_N. According to principles of the analysis of variance the statistics – F-ratio of Fisher (i.e. intergroup variance divided by common variance inside all the groups with с N–1 and $N(2M–1)$ degrees of freedom), which describes the resulting image, can be constructed.

$$F = \frac{N(2M-1)}{(N-1)2M} \frac{\sum_{n=1}^{N}\left(a_n - \frac{1}{N}\sum_{l=1}^{N} a_l\right)^2}{\sum_{n=1}^{N}(q_n^2 - a_n^2)},$$

More exactly, to the received formula some nonlinear transformation $r_{ij}=f(F_{ij})$ of "*look-up-table*" type can be applied in order to provide an acceptable to a human eye histogram of brightness. Thus, the final image is "depicted" by statistics of Fisher which acts in this case as a measure of dissimilarity between averages on various directions. In the given approach it is supposed, that the same statistics, on the basis of which the hypothesis is rejected or accepted, can be used as a quantitative measure of a deviation from exact symmetry (here from isotropy) as well and to serve as a characteristic of brightness of the resulting image.

Testing of welding on the basis of nonlinear tomosynthesis with structure-oriented filtering

Algorithms of this type were tested on the visualisation of internal structure of ferro-concrete constructions and yielded good results. [9, 10]. In the case when basic theoretical results are already received, it is fruitful to simplify them up to those limits when the based on them algorithms still work, yielding the approached practical results not so strongly distinguished from present. Variants of such procedures can be found in [10, 14, 13]. These algorithms were applied to testing of welding in components of an atomic power station [13, 14, 16-18]. In particular, a problem of crack detection in welding on filled pipelines (Fig 1) was investigated..

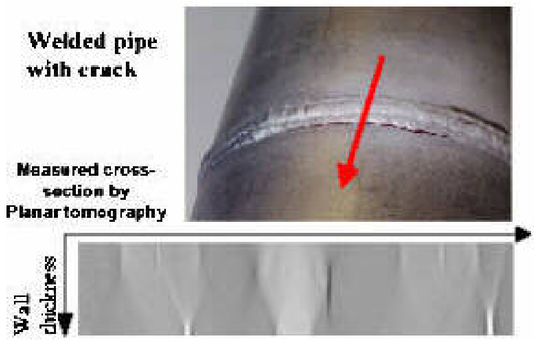

Fig. 1. The test-object is a filled by water steel pipe with welding. The diameter of pipe is 140 mm and thickness is 13 mm.

Projections (Fig. 3, Fig. 4 and Fig. 5) represent the displayed onto plane images on cylindric surface (the bottom of the projecton coincides with its top). Different projectional images are received due to shift of a source of radiation along an axis of rotation of a pipe. The angle between extreme and central projections is 10º. The geometry is easily reduced to "coplanar" as in classical томосинтезе. In doing so the parameter "depth of a layer" varies in limits from internal diameter of a pipe till its external diameter. At registration of the projectional data (Fig 2) the scanner rotates around of a pipe. About details of technical realization of the given system of tomosynthesis see [13, 16-18].

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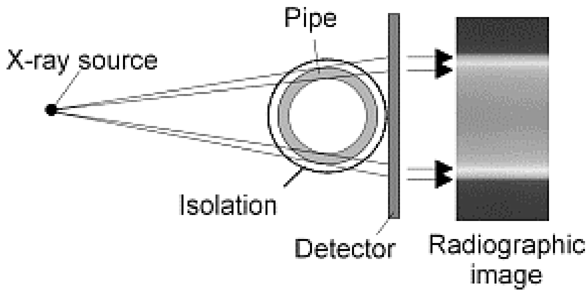

Fig. 2. Registration of projectional data (scanning of the pipe).

For visualization of formed cracks the structure oriented iltering both in spatial and in frequency areas was used. Results with application of algorithms of a spatial filtering with “sliding window” are represented.. The inherent to this filtering procedures good resolution of structural elements of a crack from the diverse information in initial image creates preconditions for satisfactory synthesis of tomograms even at relatively bad conditionality of the problem. Already three projections with a small angle of view are sufficient for reconstruction, the more so this spatial algorithms gives "rarefied" information about object, and nonlinear tomosynthesis works well on rarefied structures.

On fig. 3. one of three initial projections of test-object (a ring welding with a crack) is submitted. On fig. 4.a result of processing of this projection is represented (in the area which includes a formed crack i.e. it is a visualisation of ROI – “*region of interest”* on the basis of structure-oriented method.

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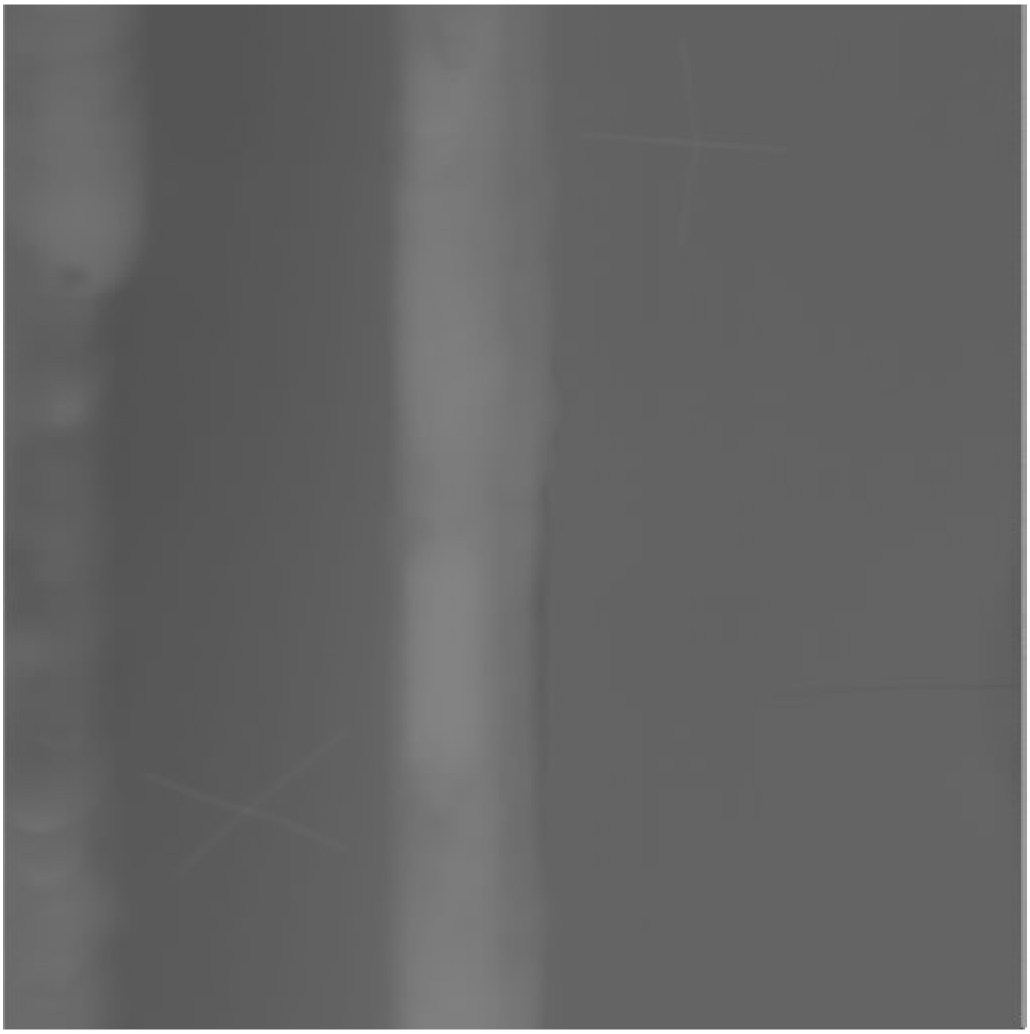

Fig.3. One of initial projections (“the right”) of ring welding in the pipe.

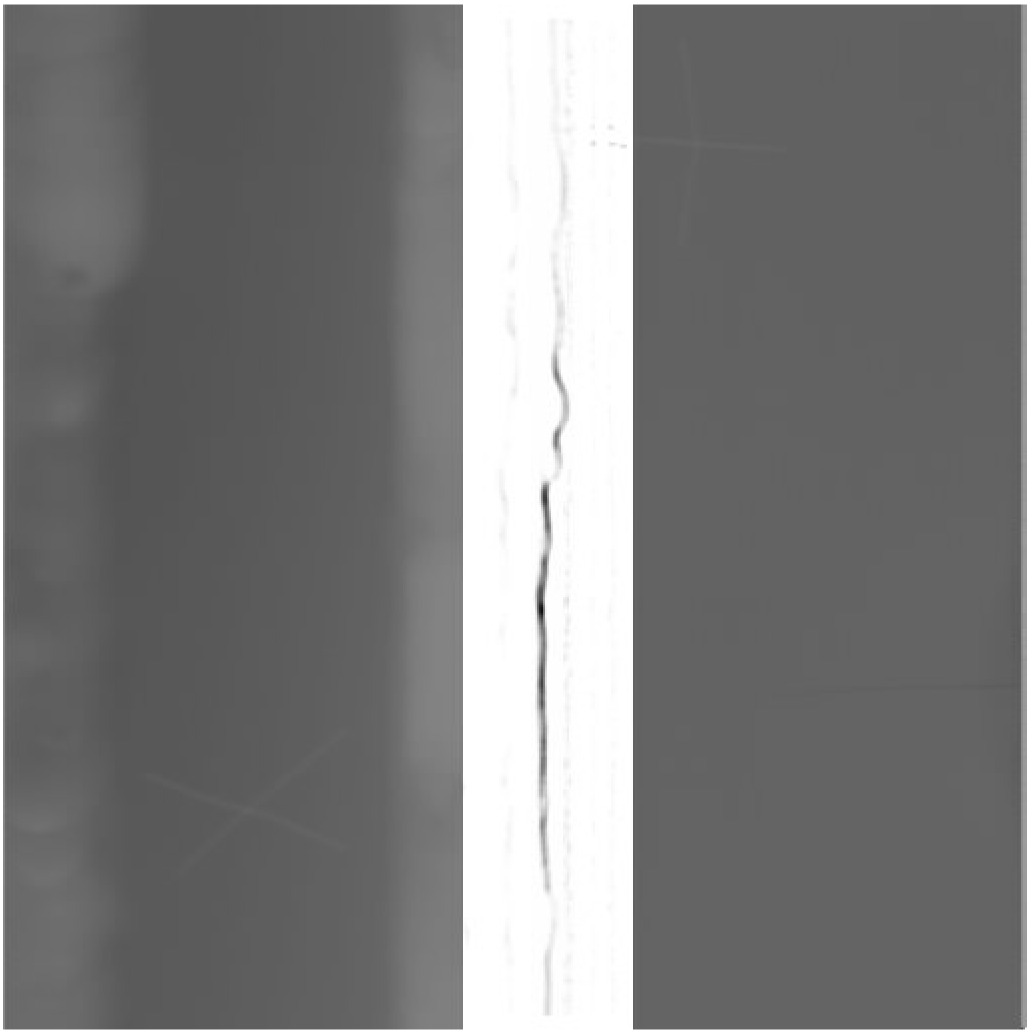

Fig 4.Structure-oriented filtering (for the “right” projection).

On Fig. 5. results of filtering of three projections are shown together for convenience of the review. On the left strips are shown the unfiltered central zones of projections. On the right strips – the filtered zones.

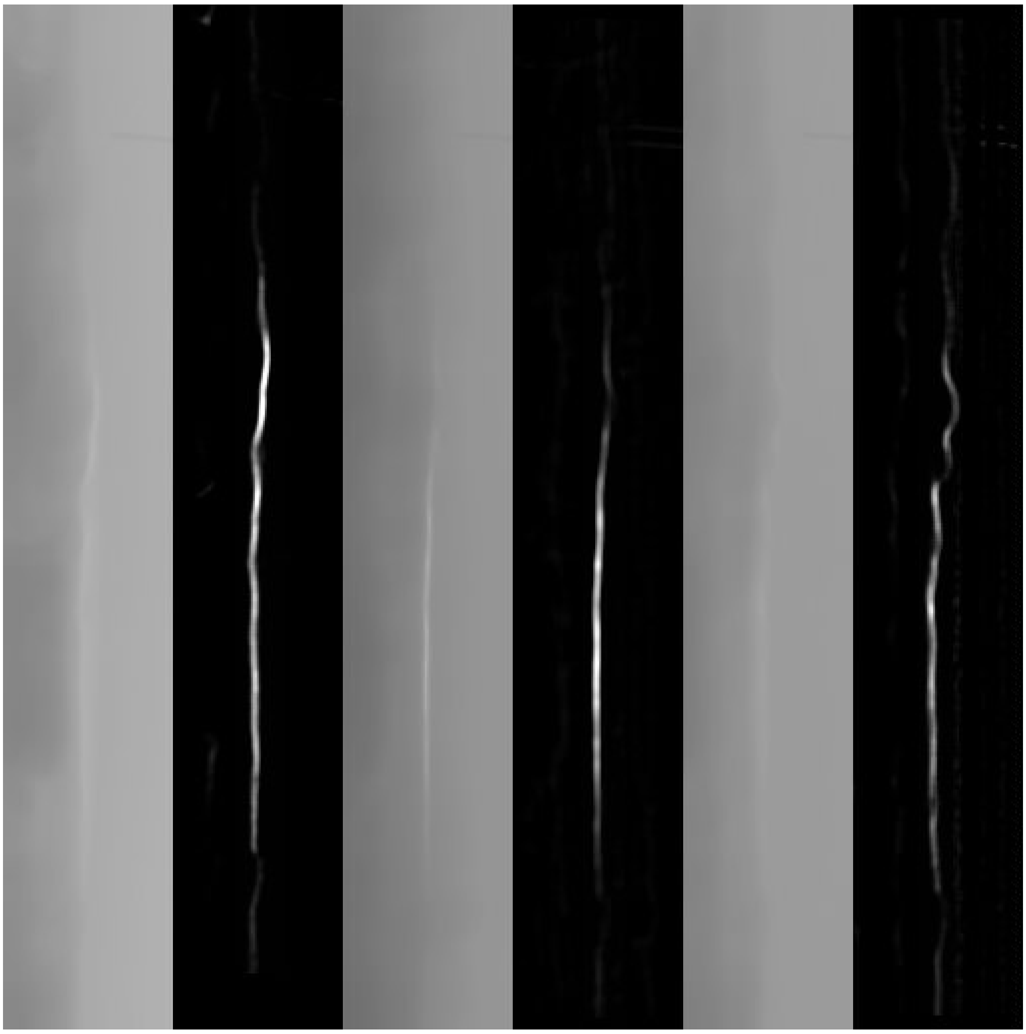

Fig. 5..Structure-oriented filtering of image of crack in ring welding for three projections (the left strips are "regions of interest" on uhfiltered projections; the right strips are the corresponded regioms on filtered projections).

On Fig. 6 the 3-dimensional image of a formed crack is represented. It is composed from 50 tomograms of sections where their depths are allocated in regular intervals from internal radius of a pipe up to its external radius. Each of tomograms was synthesized by a method of the minimal projections [7] from three projections which were preprocessed on the basid of structure-oriented method.

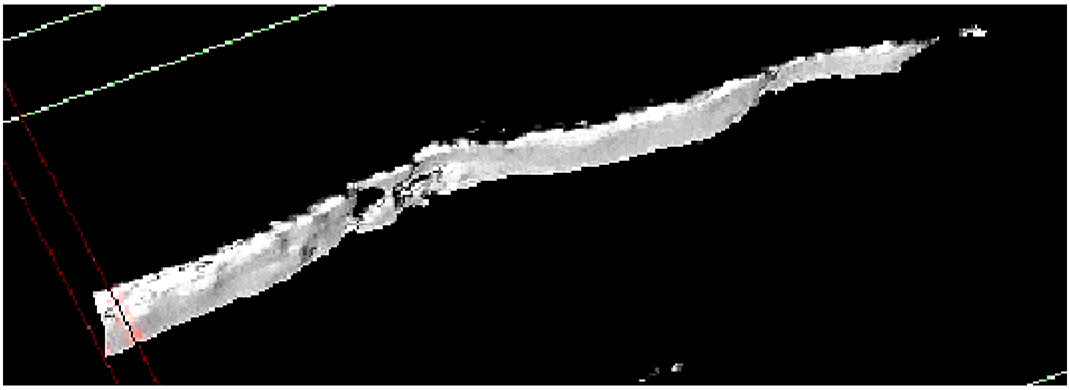

Fig.6. The 3-dimensional image of the formed crack

Conclusions

The high-sensitive radiometric camera [13, 14, 17, 18] which was used in this experiment gives for measurement of the projectional data higher quality of the image in comparison with film radiography. Measurements were carried out repeatedly both on the nuclear power station, and in laboratory conditions. The substantial improvement of quality of the image of water-filled pipes is achieved – the same as film radiography gives for empty pipes. Methods of nonlinear tomosynthesis are essential to interpretation of measurements, and new structure-oriented procedures — for revealing of cracks under formation and for their morphological analysis. The predictive value of a method is caused just by them.. Nonlinear tomosynthesis with special image processing allowes not only to enhance the detectability of zones of formation of cracks and to take more information on their form, the sizes, separated fragments etc., but also to estimate their depth as well as depths of separated fragments of these zones. It is necessary to note, that accuracy of definition of these parameters can be essentially raised on the basis of the statistical methods which are developed specially for this purpose.

Nonlinear tomosynthesis was successfully applied to traditional by the most difficult, (and until recently "unsolvable" problems) of radiation testing. The success of this method in much is caused in much by the unified approach to at first sight diverse problems, and also by the advanced and natural mathematical apparatus which is easily adjustable to the type of test-object. The methods of structure-oriented image processing are also efficient for the morphological analysis of images

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