EXPERIENCE OF "INDINTRO" COMPANY IN INDUSTRIAL X-RAY TOMOGRAPHY

Vaynberg E.I., Vaynberg I.A., Tsyganov S.G., Sharov M.M.
INDINTRO Co., Ltd., Moscow, Russia, indintro@vei.ru

During last two decades, the industrial X-ray computed tomography (CT) systems became the habitual (customary) tool for development of new technologies and reliability augmentation of critical products of aerospace, automotive and defensive industries of the leading industrial countries [1-4].

At the same time, if to compare a modern level of development of technique and market of industrial computed tomography (CT) with the successes of its "primogenitor" - a medical computed tomography, a more modest estimation of long achievements of industrial tomography is inevitable.

There are three basic reasons:

- "inconvenient" (for multi-angle X-raying) physical characteristics of industrial objects of the testing (high density and effective atomic quantity, as well a wide range of the sizes and weights of products) and their inadequacy with technical parameters of modern sources of braking radiation: penetration capability of radiation [5], the sizes of focal spot, and exposure rate;
- very small sizes and admissible errors of geometry measurement of the structural defects, which are a subject of detection;
- a limited market of innovative technologies of responsible industrial products of aerospace, automobile, and defense applications.

These fundamental factors determine a modern condition and directions of development of industrial tomography, first of all as **high-energy** and **minifocal** CT.

Figure 1 shows the several models of high-energy industrial CT systems of "INDINTRO" Company with maximal diameters of tomograms from **500mm** up to **800mm**, weight of test objects from **300**kg up to **1000**kg and length of vertical moving more than **1**m**.** Two sources of radiation are used in each of the presented systems: a **450kV** X-ray tube and electron accelerator with energy of **5MeV**, in a combination with additional collimators, which control the sizes of effective focal spot and minimize a level of afocal radiation. Penetration capability of these CT systems for steel is not less **150**mm, a limit of spatial resolution in all energy range is **50** line pairs/cm and accuracy of size measurement of internal structural elements is **0,05**mm. A technique of a local tomography is used with a format of reconstructed general and local tomograms up to **2048x2048** at adequate increasing a quantity of projections.

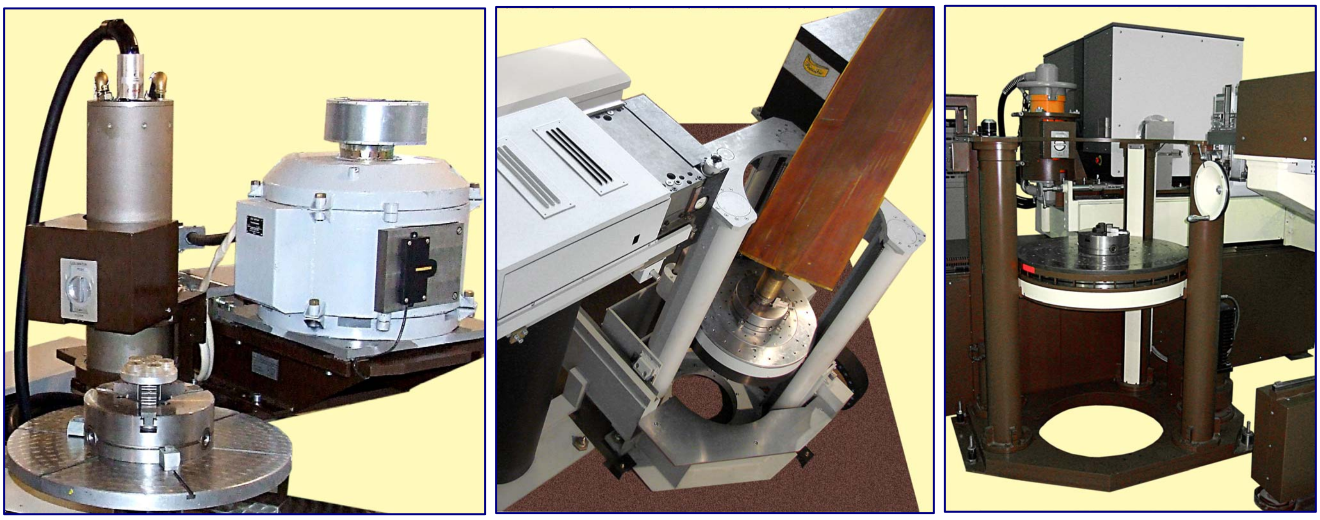

Fig. 1. Three high-energy CT systems of "INDINTRO" Company

Despite a limited resolution of format A4 and standard monitors, the presented here CT images give a representation about a high results quality of CT testing by these systems.

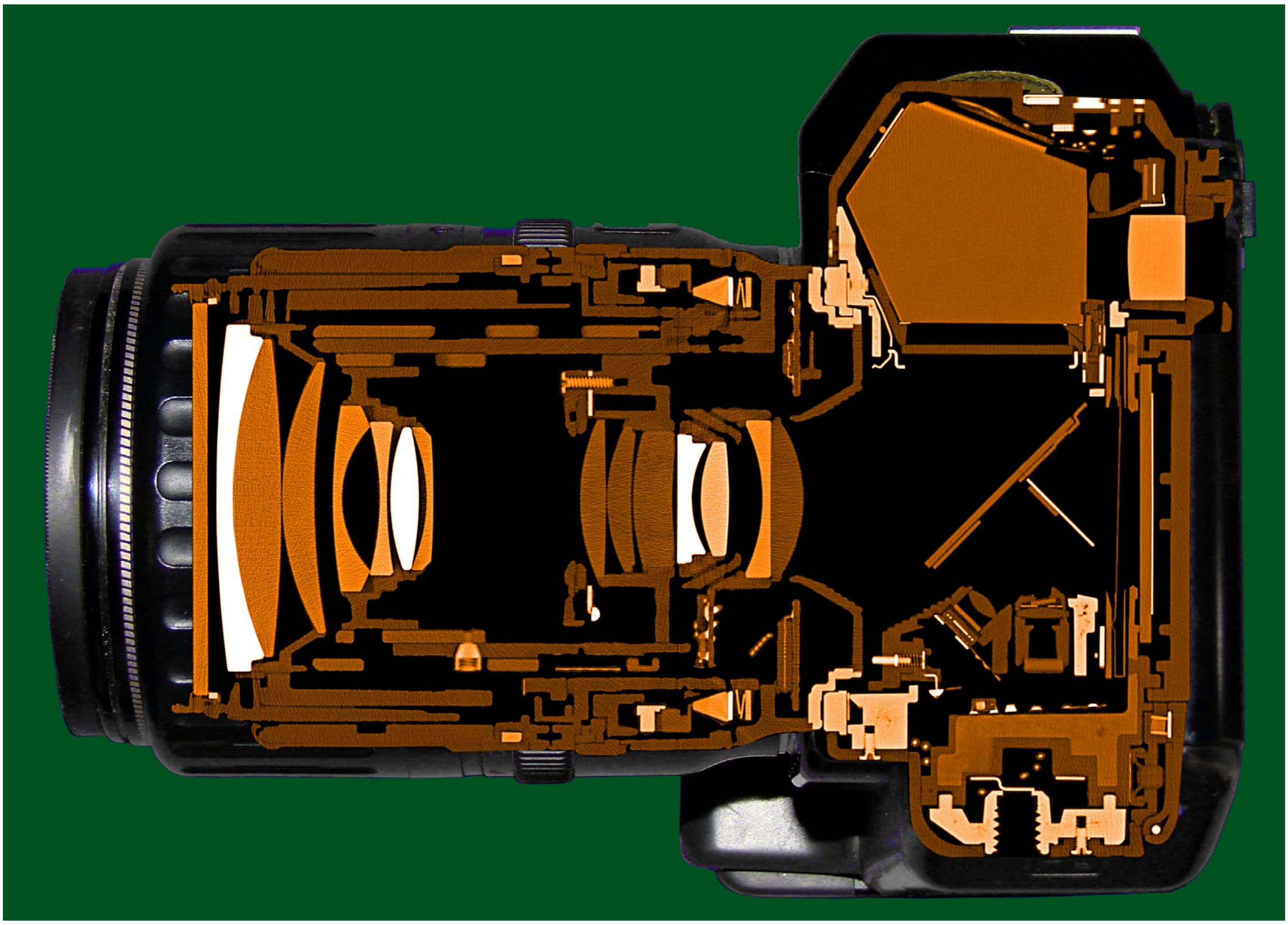

Fig. 2. CT image of longitudinal section of Mr. Guiseppe Nardony’s reflex camera

The main application fields of industrial CT systems are measurement of sizes and density distribution inside of the complex metal and dielectric parts, assemblies, and multilayered composite structures, inspection of which by means of radiography, ultrasonic defectoscopy or other traditional NDT methods is inefficient because of structure complexity of test objects.

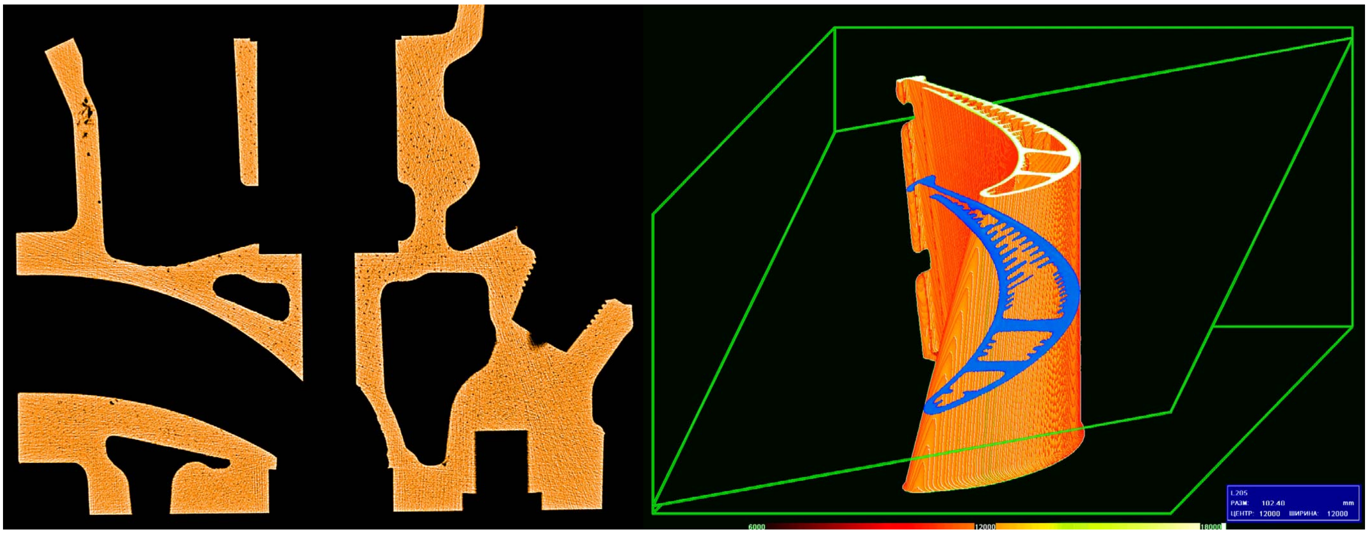

Fig. 3. CT image of a head of cylinder block and 3D image of a turbine blade

Typical examples of application of CT systems are the following: flaw detection of complex castings; technology development, measurement of wall thickness and geometry of internal structure of cooled turbine blades of gas-turbine engines; non-destructive testing of complex welded, soldered, and glued connections, composite vanes and elements of aircraft structures; flaw detection of catalytic neutralizers, heads of cylinder block, and automatic gearboxes of cars; diagnostics of

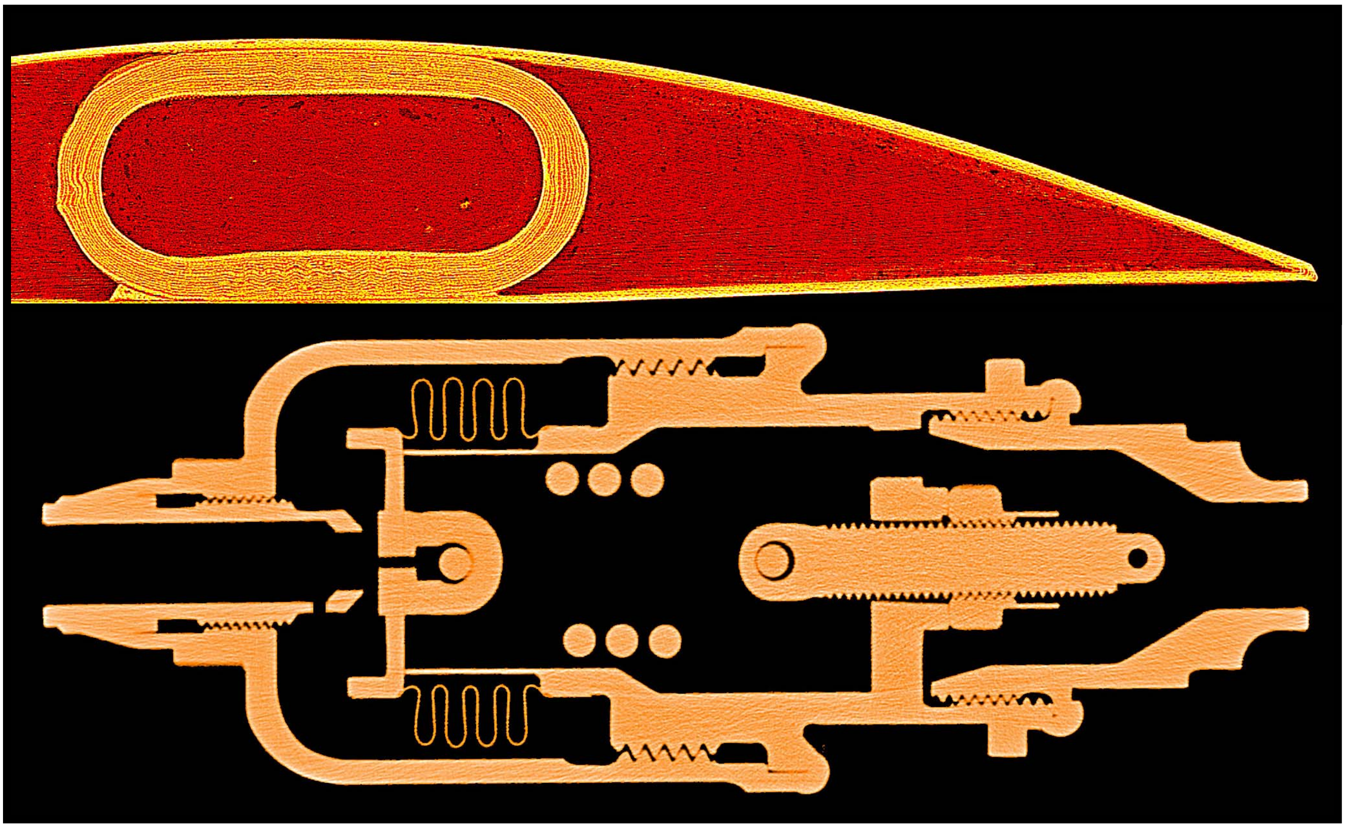

Fig. 4. CT images of composite vane and sealed steel valve

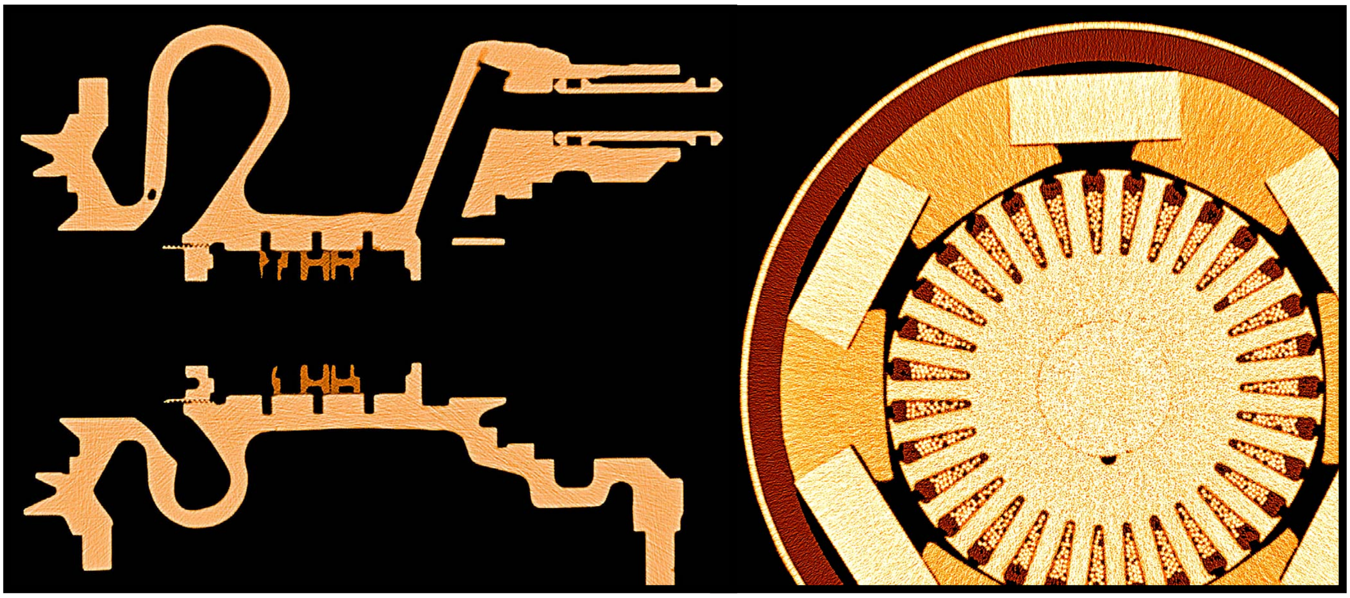

Fig. 5. CT images of steel airframe of liquid-fuel rocket engine and electric motor

assemblage correctness, and density deviations of high-effective ammunition; certification of the critical elements of space technics: heat-shieldings, fairings, turbine wheels, valves, navigation and pyroelectric devices; defectoscopy of composite nozzle clusters and combustors of solid missile; flaw detection of important rubber-cord products; technology development and certification of crucial products made of graphite and reinforced carbon-carbon composites; flaw detection of electrochemical current sources; diagnostics of fuel elements and assemblies; certification of power semiconductor modules and switching electrical facilities; certification of mineral raw material; and a lot of other things.

Fig. 6. CT images of honeycomb heat-protection block and carbon-carbon composite nozzle cluster

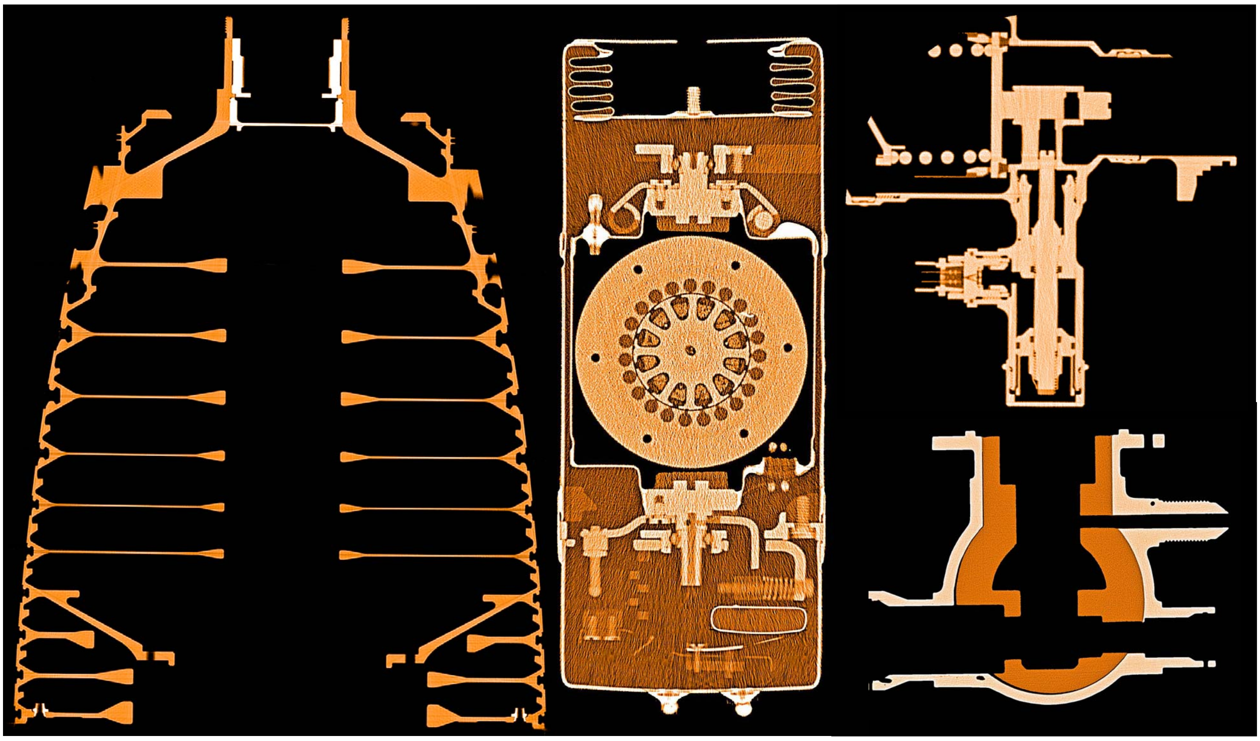

Fig. 7. CT images of aerospace unit, gyro pickoff and valves

Necessity of X-raying of test object in a classical tomography over a full range of angles $180(360)^0$ highlights a problem of small penetration capability of a braking radiation with reference to heavy large-sized products.

For example, steel (ρ ~**7,8**g/cm^3; Z~**26**) cast products, which have even in one of directions a total thickness more than **350**mm, are practically non-testable for computed tomography. It is truth that for large, but thin-walled steel and titanium products (ρ ~**4,5**g/cm^3; Z~**22**), for aluminum castings (ρ ~**2,7**g/cm^3; Z~**13**), and composites the situation is more optimistic. However, other approaches are necessary for creation of CT systems for heavy-walled massive steel castings and assemblies with going beyond of a classical tomography and (or) braking radiation.

For comparison we shall remind that in a medical X-ray tomography physical properties of test object (ρ~**1**g/cm^3; Z~**7,5**) are essentially more adequate to penetrating capability of braking radiation, and for diagnostics of a most dense medical object – human head ~ **20**cm in diameter - a voltage **120kV** is enough.

In view of a significant value and inhomogeneous of attenuation of direct braking radiation by industrial test objects, a quality of CT images and accuracy of tomographic measurements depend essentially from wide energy spectrum of X-ray beam and high background of scattering radiation. Therefore, an additional filtration of radiation and maximal collimation of the input apertures of each channel of detection are important conditions of achievement of high quality and accuracy of tomographic testing. For example, searching the decisions on significant attenuation of contribution of scattered radiation at using the high-energy flat panel detectors is a key problem of their efficiency in industrial tomography.

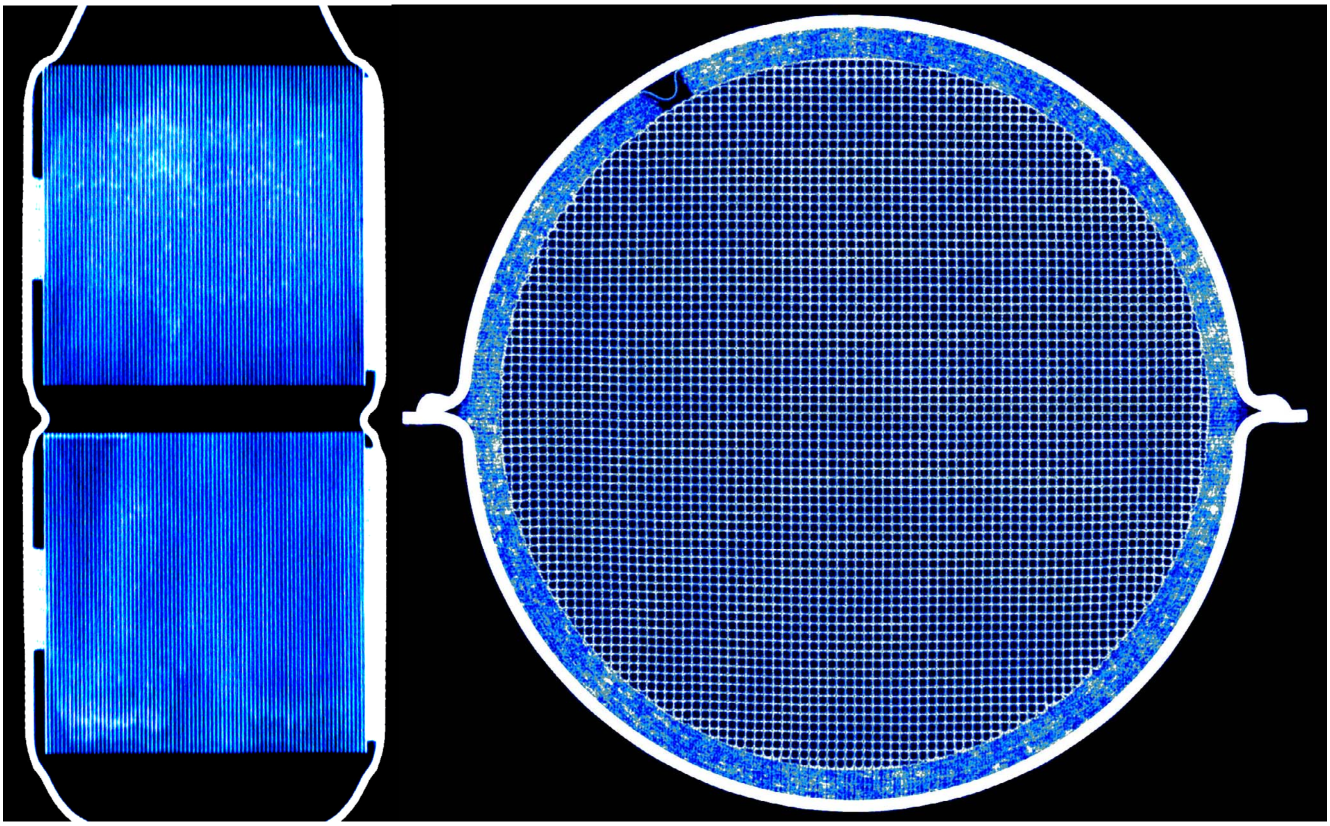

Fig. 8. CT images of longitudinal and cross sections of catalytic neutralizer

Increase of the spatial resolution of industrial CT systems is major direction of improvement of sensitivity to local defects in the form of pores and inclusions as well as for augmentation of accuracy of sizing the elements of complex inner structure. Therefore, a modern high-quality CT image of industrial test object contains already up to **2048x2048** calculated values. Moreover, due to using a technique of local tomography [6], ratio of diameter of test object and minimally resolved element of CT image (D/Δl) can exceed 10^4. Here the industrial CT systems have surpassed a medical X-ray tomography, for which a format of reconstructed CT images of **512x512** is standard at visualization with interpolation up to 1024 x 1024.

Nevertheless, the further perfection of industrial CT systems will demand greater value D/Δl, and, hence, proportional increasing a quantity of angular projections, quadratic growth of the CT image file size, and cubic growth of quantity of reconstruction operations.

The major condition of achievement of the high spatial resolution is a development of new minifocal (~ 0.2mm) sources of braking radiation with energy from 1.5MeV to 5MeV and increased exposure rate (in some tens times).

Prospects of significant increasing a productivity of industrial CT systems are available with using an experience of medical multilayered helical CT systems. Nevertheless, researches of dynamics of volumetric destruction, explosions or others aperiodic quick processes in present time remain inaccessible for industrial tomography because of requirement of data acquisition under many angles.

In connection with continuous increasing a data volume of the 2D and 3D results of tomographic testing, a transition from interactive decoding the CT images by skilled operator to automatic diagnostics with formation of final report and a quantitative estimation of conformity of CT results to the requirements of design documentation of test object is inevitable.

Automation of a full cycle of quantitative CT diagnostics is most reasonable for specialized CT systems of narrow range of products. That will raise a testing productivity and will lower result dependence from a "human" factor.

Unfortunately, effect of automation eases a role of visualization means of CT images, acquisition costs of 2D and 3D graphics, and operator's functions. The beauty of a computed tomography yields to rationality of digital estimations.

Thus, industrial X-ray CT systems have entered into a period of maturity and the further directions of their evolution are determined by fundamental factors.

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