Computed Tomography – a highly potential tool for industrial quality control and production near measurements

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Abstract:

Computed tomography (CT) using x-rays, originally developed to visualise inner human structure, has become an important tool for industrial applications. CT systems are at present not only used for the non-destructive defect analysis of parts. Only a few years ago CT started to be used for dimensional measurements. It is the only way to measure the inner and outer geometry of parts in a non-destructive way and with high data density. The article demonstrates the spread of applications of CT for quality control and production near measurements by selected examples. A drawback of CT is at present that measurement deviations caused by complex influence factors often cannot be quantified. Nevertheless, concepts exist to analyse measurement deviations and to correct them. One example is the correction of scaling factors e.g. by the measurement of reference bodies. For selected measurement tasks ISO/TS 15530-3 can be utilised to determine the measurement uncertainty.

1. Introduction

Computed tomography (CT) has been developed 30 years ago as a medical imaging technique. Since 20 years industrial applications of CT exist. Nowadays, the design of industrial CT systems differs significantly from medical CT systems: In nearly all industrial systems the object (workpiece) is rotated on a rotary table (Fig. 1).

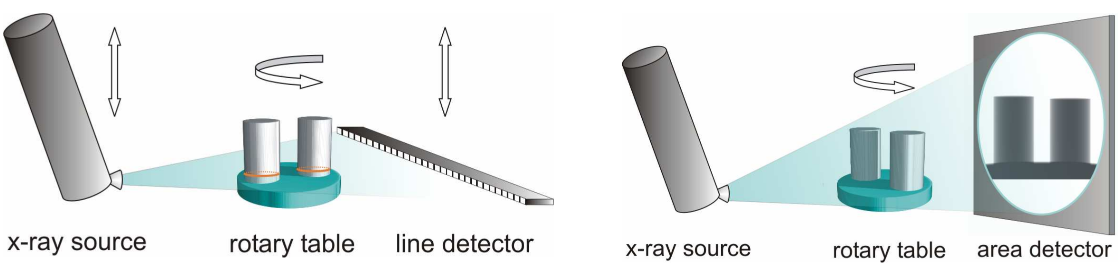

Fig. 1: Industrial CT scanning: Principle of 2D-CT (left) and 3D-CT (right) scanning systems

CT imaging is used in its classical technical applications to detect faults inside workpieces non-destructively [1] and has gained a high importance for the quality control of security relevant parts, for racing applications, for casting defect analysis and for semiconductor checking to name a few examples (Fig. 2). New applications of industrial CT are the analysis of fluid flows or fat content determination of meat or the analysis of the germination capacity of crops in the food industry.

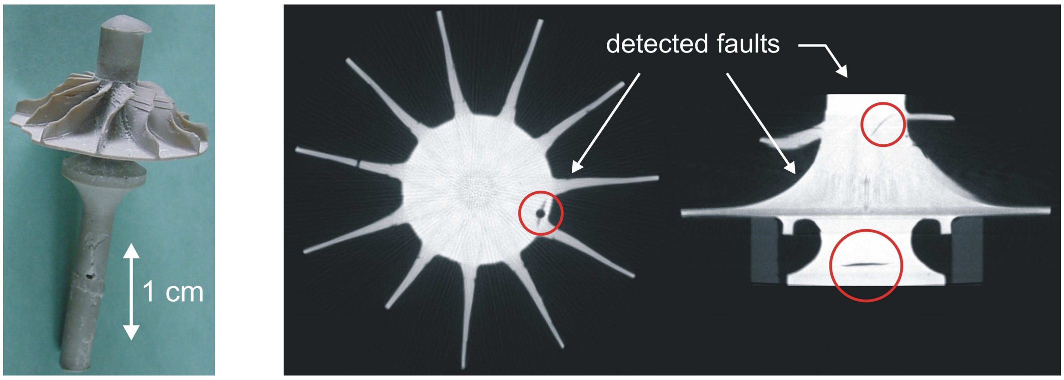

Fig. 2: CT used to detect faults in industrial parts. Example: micro turbine; left: Photography; right: Slice images achieved by CT scanning which reveal faults inside the part. Source: Bundesanstalt für Materialforschung und –prüfung BAM, Berlin, Germany

An enhancement to the classical defect analysis with CT is the automatic detection of faults (Fig. 3). Dedicated software packages are applied to isolate defects from the bulk material and to classify them. CT starts to be used here as a quantitative measurement method.

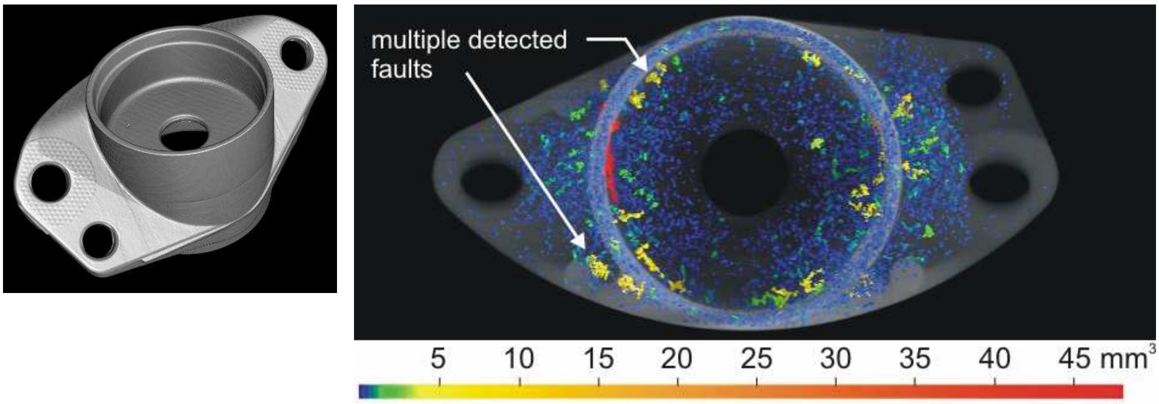

Fig. 3: Automatic detection of faults inside an aluminium-cast part; left: CT measured data; right: Detected faults, grey scale values (colours) indicate fault volume. Source: Volume Graphics, Heidelberg, Germany

Currently two different types of industrial CT systems are in use: 2D-CT systems utilise a fan beam and a line detector (Fig. 1 left), whereas 3D-CT systems are equipped with a cone beam and an area detector (Fig. 1 right). Both types yield full 3D information of the work-piece. CT systems with x-ray tubes up to 450 kV acceleration voltage can penetrate up to

300 mm aluminium [2] for defect analysis. CT systems with micro-focus x-ray tubes (usually up to 225 kV) can yield spatial resolutions down to the order of $(2\ \mu m)^3$ expressed by the voxel size (size of measured cubic volume element) for workpieces in the millimetre range [3].

2. Dimensional measurement applications of CT

CT data contain the complete volumetric information about the measured body. By identification of surfaces CT is able to determine coordinates of the measured body, i.e. CT can perform dimensional measurements like coordinate measuring machines (CMMs). Since some years CT is increasingly used in industry for dimensional measurements [2]. Applications are focussed here on the absolute determination of geometrical features like wall thicknesses or on the comparison of the measured geometry with reference data sets. In most cases nominal CAD data of the part are used as reference. For some applications data from optical scanning systems are used, too. The process chain includes the following principal steps:

1. CT measurement (with numerous parameters) yielding volumetric data
2. Determination of surfaces from the volumetric data (threshold parameter required)
3. Optionally reduction of surface data size (i.e. reduction of point number)
4. Analysis of surface data with a CAD data package for absolute measurements and comparisons. Comparisons require the registration and the alignment of data sets.

3. Enhancing the accuracy of CT measurements

Usually systematic deviations are present in dimensional CT measurements. These deviations result in particular from axis guiding errors, from the finite size of the x-ray tube spot, from the detector characteristics, from energy dependent x-ray absorption within the part (beamhardening) [4], from the discrete sampling of CT projections, or from further imperfections in the system setup. Examples of important measurement deviations are scaling factors in all space directions, errors caused by the threshold determination process or systematic offsets of the measured surface position due to roughness. These deviations can be analysed with adapted reference bodies and hence corrected (Fig. 4). Different reference bodies made of aluminium, ceramics, granite and aluminium cast parts have been developed to measure and correct systematic deviations of CT [5, 6]. For the determination of scaling factors a ball bar (Fig. 4 left) has specific advantages. The distance of spheres is nearly independent of the threshold applied for the surface extraction and it is given as a fitted parameter over multiple measurement points. Scaling factors up to 1.01 have been observed on different CT systems as relative length measurement errors, i.e. a part of 100 mm length is measured with a measurement deviation of up to 1 mm!

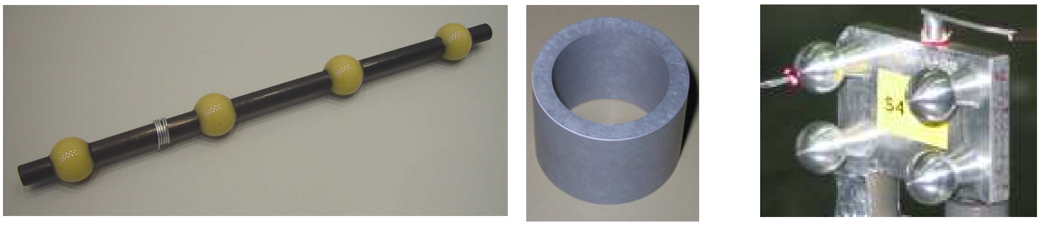

Fig. 4: Reference bodies for CT measurements [5, 6]; left: Ball bar with ceramic spheres; middle: Aluminium ring gage with precision inner and outer cylinder surfaces; right: Roughness reference body with attached 4 spheres for alignment and registration

Scaling factors are observed to change in time (Fig. 5) due to changes in the system geometry. The order of the effect requires an assessment during the respective measurement, i.e. a ball bar is measured simultaneously together with the part under study.

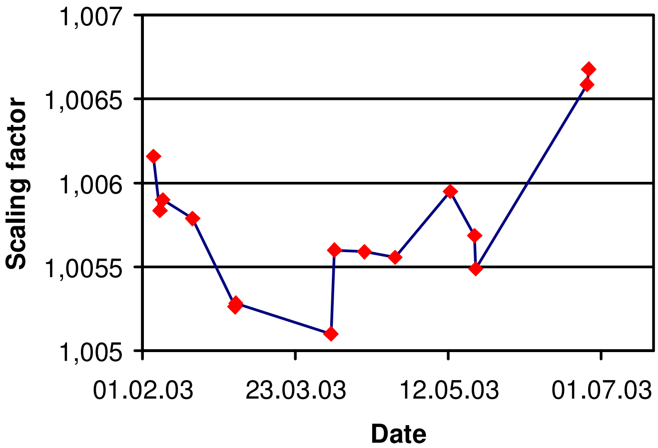

Fig. 5: Change of the scaling factor in time of an industrial 450 kV 2D-CT system

The threshold for the surface generation from the volumetric CT data can be determined by the use of hollow cylinders with calibrated inner and outer diameter (Fig. 4 middle). Application of scaling factor correction and enhanced threshold determination both could reduce position deviations of single data points to 0.1 mm for 450 kV 2D-CT measurements of well conditioned workpieces (e.g. aluminium-cast parts of <170 mm penetrated thickness [5]). Roughness induced offsets of the measured surfaces are a further deviation which can be quantified with adapted reference bodies. Reference bodies carrying a rough cast surface and elements for alignment and registration have been successfully used to quantify the offset [6]. Corrections of this and of further systematic effects are topics for running activities. The enhancements achieved up to know have reduced the measurement uncertainty of dimensional CT measurements and enable a systematic uncertainty treatment as explained in the following.

4. Outlook for the uncertainty evaluation of CT according to ISO/TS 15530-3

The task-specific measurement uncertainty of CT currently cannot be fully quantified. This is due to complex influence factors from the CT hardware and software and from the workpiece itself. Analytic uncertainty budgets do not exist. A potential solution is to follow the approach of ISO/TS 15530-3 [7], i.e. to use calibrated workpieces to determine the task-specific uncertainty. ISO/TS 15530-3 asks to perform the following steps:

1. Calibration of at least one workpiece with standard calibration uncertainty u_{cal}
2. Determination of standard deviation u_p of the repeated measurement process
3. Determination of the standard uncertainty u_w due to the spread of workpiece features (thermal expansion coefficient, form deviation, roughness, etc.)
4. Determination of systematic offset b between measurement and calibration
5. Calculation of measurement uncertainty $U = k \times \sqrt{u_{cal}^2 + u_p^2 + u_w^2} + |b|$

   with expansion factor k (for 95% coverage of U; in most practical cases $k = 2$)

When applying the concept, an essential problem is the difference in the probing pattern between tactile CMM and CT. CMM calibration values are related to specific points on the surface and mechanically filtered by the probing sphere. In contrast, the CT results average locally over the surface profile. A systematic difference may result from this and increase b. The offset b additionally depends on the threshold value used to generate surfaces from the volumetric CT data. These aspects have to be kept in mind for function-related tolerancing of parts, e.g. for the complementary cases of shaft/hole fits or for flow rate conditioning geometries. In a first experiment with a 450 kV 2D-CT, an actual-nominal value comparison on an aluminium-cast part (size 150 mm x 100 mm x 300 mm), the standard deviation u_p for a single surface point was found to be in a range from 0.01 mm to 0.082 mm with an average of 0.038 mm. For 95% of all measured points u_p is smaller than 0.064 mm. Measurements have been performed on 130 points distributed over the part. The influence of roughness and its impact on u_w can be assessed with roughness reference bodies (Fig. 4 right). For a 450 kV 2D-CT system measuring aluminium-cast part (roughness R_z = 50-210 µm) an u_w= 50 µm has been estimated using measurements of 3 roughness reference bodies [6]. The results are a positive indicator for the feasibility of task-specific uncertainty statements. A rigorous study of the measurement uncertainty for measurements of cast parts is currently running.

5. Summary and outlook

Industrial computed tomography is one of the most versatile and powerful non-destructive evaluation techniques both for defect analysis and for dimensional measurements. CT systems will in future be increasingly used for universal dimensional measurement tasks – like CMMs today. First initial sample approvals for cast products are a clear indication of this. The process chain for dimensional measurements using CT should include the analysis of systematic deviations either for correction or for verification. Present process chains need to be further adapted to ensure more traceable dimensional measurements. The results available up to now indicate — under specified conditions — the suitability of measurement uncertainty analysis for dimensional CT measurements according to ISO 15530-3. Measurement uncertainties for measuring large parts with 450 kV CT systems of the order of 50 µm are struck for a goal. Respective measurement uncertainties for measurements of small parts in the millimetre range with micro-focus CT systems of the order of 1 µm are aimed at.

Acknowledgement

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