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Thermal influences on X-ray source position in X-ray computed tomography

Marko Katić[1], Nenad Ferdelji[1], Danijel Šestan[1]

[1]*Faculty of mechanical engineering and naval architecture, University of Zagreb*

marko.katic@fsb.hr

Abstract

X-ray computed tomography (XCT) is becoming widely adopted for dimensional metrology tasks in various industrial sectors, primarily because it enables measurements of hidden / inaccessible geometry. Traceability of results obtained using XCT is difficult to establish, due to difficulties associated with numerous error sources which are not well-known. Standardization efforts, such as VDI/VDE 2630 rely primarily on substitution methods, circumventing a more detailed analysis of error sources. As previous research has shown, thermal influences are typically some of the largest sources of measurement errors in XCT. Thermal expansion of the X-ray source is especially significant, as it causes a displacement of the focal spot position and therefore directly influences the metrology loop of the system. In this paper, we present the methodology which applies to the X-ray source as a black-box in order to characterise the heat sources it contains. High-accuracy temperature sensors were used to determine the temperatures of various parts of the X-ray source, at different X-ray power levels, while simultaneously tracking the position of a precision sphere at high magnification. These results are used to determine the thermal constants of the system which can be used to establish the correct warm-up time and avoid significant displacements of the focal spot during the XCT measurement. In order to estimate the amount of focal spot displacement as a function of X-ray power, which can then be used to apply corrections to the measured data, a further analysis is also presented. Initial boundary conditions are calculated using 1D analytical methods, which then serve as an input in a CFD analysis of the entire XCT system.

Keywords: X-ray computed tomography, thermal influences, accuracy

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1. Introduction

High-accuracy XCT metrology is being increasingly used in different applications, with additive manufacturing as one of the most important technologies which rely on XCT for quality control. In its core XCT is a relatively simple optical system, where a point-source projects a cone beam of X-rays on a digital detector (Figure 1). Cone beam geometry results with a magnification (M) of the sample, which depends on the distance between the source and detector (SDD) and distance between source and sample (SSD), according to the formula *M = SDD / SSD*.

Numerous research has been focused on establishing the traceability of XCT measurement results to the SI definition of metre during the last few years, and one of the results was the adoption of VDI/VDE 2630 standard which can be used to estimate the measurement uncertainty of XCT results. This is a substitution method for experimental determination of measurement uncertainty similar to approach in ISO/TS 15530 which targets Coordinate Measuring Machines (CMM), where measurement uncertainty is described in terms of repeatability and bias. In XCT, bias itself could be attributed to shifts in magnification due to displacement of the focal spot (if all other parameters are kept constant), which changes the SDD value. Focal spot shifts can occur due to instabilities related to magnetic lens which focus the electrons to the X-ray source, or due to thermal expansion of the X-ray tube; possibly both. Research presented here focuses on the thermal issues, as large temperature gradients are known to occur at the X-ray tube. Usually, heat sources within X-ray tube are not defined by manufacturers (proprietary data) - only the electrical power used to generate X-rays is known, but for example power of magnetic focusing coils is typically unknown. For this reason, we used temperature data to estimate the values of additional power sources in the X-ray tube using 1D analytical functions, and subsequently used these values for a more detailed CFD simulation which provides calculated focal spot displacement under various X-ray power levels.

2. Temperature and displacement measurement

Previous research already showed that significant changes in temperature occur during operation of an XCT scanner, with largest changes at the X-ray tube. The research presented here therefore focuses on the X-ray tube in more detail, with eight high accuracy thermistors placed at different locations on the X-ray tube. Temperature measurements were performed at four different X-ray power levels: 10 W, 20 W, 30 W and 40 W. Prior to all measurements, stable conditions were ensured with X-rays turned off for at least eight hours. During each measurement a series of 2D radiographs were acquired of a precision sphere with a diameter of 100 µm placed at the highest achievable magnification (i.e., as close as possible to the X-ray source). Under the assumption that the sphere's mechanical position remained stable for the duration of the measurement, any movement of its centre position can be attributed to displacement of the X-ray focal spot - caused either by thermal,

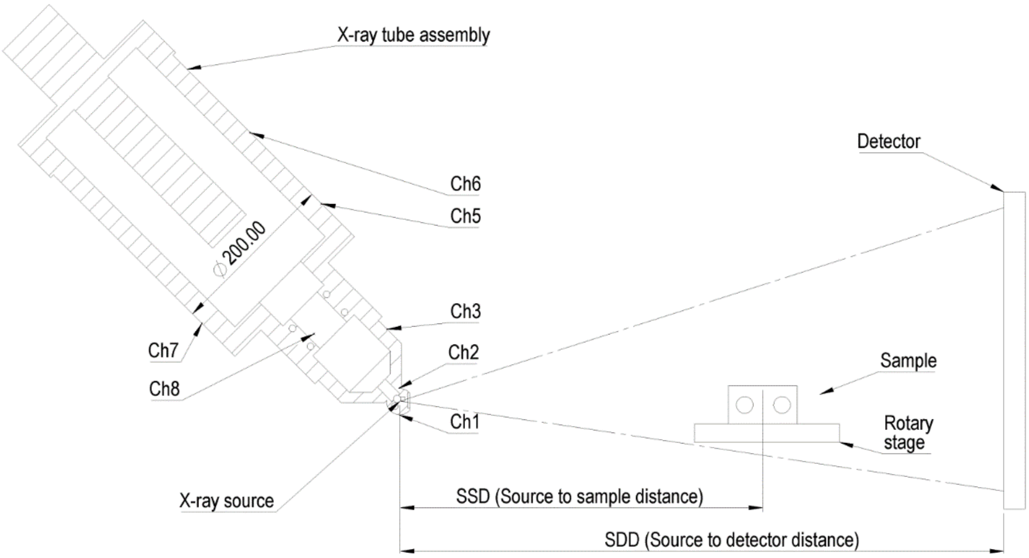

Figure 1. Schematic representation of cone-beam industrial XCT.

magnetic, or a combination of those influences. Sphere centre was determined using standard thresholding algorithms (ImageJ). Temperature measurement results are shown in Figures 2-5. Figure 6 shows the temporal relationship of calculated X-ray source displacement with respect to temperature measured at location 2, for 40 W X-ray power level. Data from Figure 6 indicates that there is good correlation between temperature and Y-displacement, which leads to conclusion that almost entire displacement of X-ray source can be attributed to thermal influences.

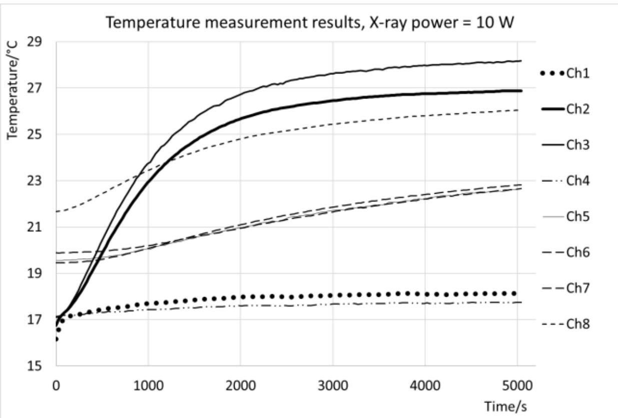

Figure 2. Temperature measurements, P = 10 W.

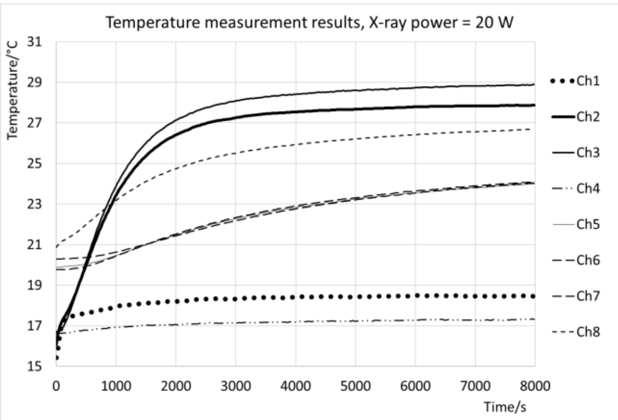

Figure 3. Temperature measurements, P = 20 W.

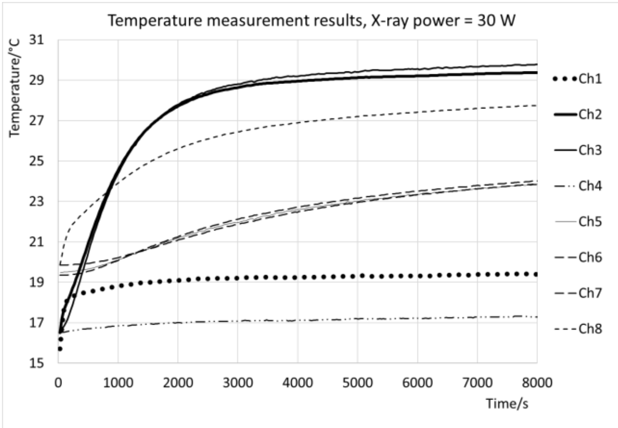

Figure 4. Temperature measurements, P = 30 W.

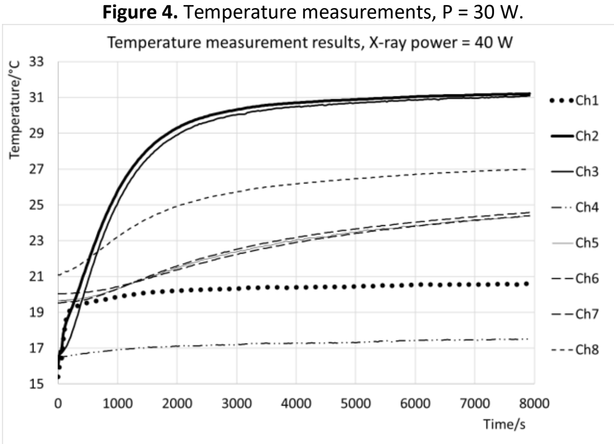

Figure 5. Temperature measurements, P = 40 W.

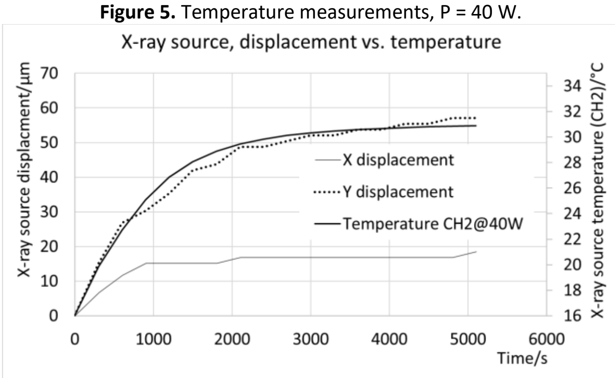

Figure 6. Temperature and displacement of X-ray source, P = 40 W.

3. Estimation of unknown heat fluxes

The first step in modelling displacements and its corrections, the unknown heat fluxes inside the CT source tube should be estimated based on observed temperature profiles. Since the model, for the purpose of further development, should be fast and relatively simple, a 1D transient heat conduction model is applied to each cross section with available measurement results. The model assumes a hollow cylinder with two boundary conditions: a heat flux density at inner radius and heat transfer coefficient with corresponding air bulk temperature at outer radius. Since all existing heat fluxes causing observed temperature profiles are unknown, heat flux density at inner radius represents all incoming heat fluxes while boundary condition of third kind at outer radius represents all outgoing heat fluxes transferred by convection and conduction through the tube material. Analytical model for non-dimensional temperature of the proposed model profile can be easily derived in a form of infinite series as a function of Biot and Fourier numbers:

$$\Theta = \frac{r_1}{r_2}\left(\frac{1}{Bi} - \ln\frac{r}{r_2}\right) + \sum_{n=1}^{\infty} A_n\, \phi_n(r)\, e^{-\lambda_n^2 Fo}$$

where A_n is a known coefficient and f_n depend on eigenvalues l_n found as n-th root of the following function in which J_n and Y_n are Bessel functions of first and second kind, respectively:

$$\lambda_n\left[J_1(\lambda_n)Y_1\left(\lambda_n\frac{r_1}{r_2}\right) - J_1\left(\lambda_n\frac{r_1}{r_2}\right)Y_1(\lambda_n)\right] = Bi\left[J_0(\lambda_n)Y_1\left(\lambda_n\frac{r_1}{r_2}\right) - J_1\left(\lambda_n\frac{r_1}{r_2}\right)Y_0(\lambda_n)\right]$$

Knowing air bulk temperature as well as tube material properties only two parameters should be varied to match simulated and observed temperature profiles: a heat flux density at inner radius and a heat transfer coefficient at outer radius. The curve fit method used is a least square method applied to fit only upper and lower tail of temperature curve, i.e., data used for fitting procedure are defined by Fo number satisfying following conditions: $Fo < Fo_{\min}$ and $Fo > Fo_{\max}$ where $Fo_{\min}$ represent upper bound of lower tail and $Fo_{\max}$ represents lower bound of upper tail of temperature profile. Since every part of the CT tube has a different characteristic time constant, $Fo_{\min}$ and $Fo_{\max}$ differs for each observed temperature profile.

Simulation results are given below for thermistor Ch3 and Ch7 in Figures 7 and 8. Since simulated profiles show a very good match with the measurement data on both tails, simulation results can be used to estimate unknown heat fluxes for further processing.

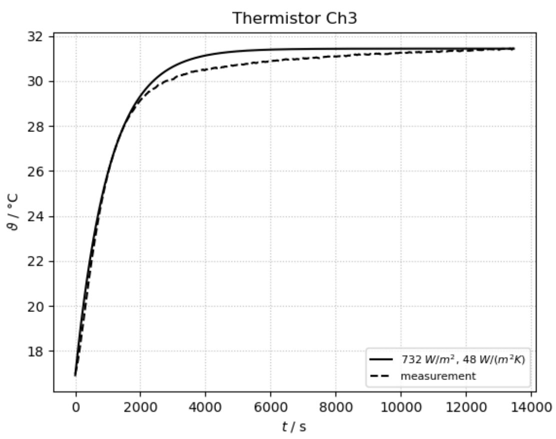

Figure 7. Comparison of measured and simulated data for thermistor at position 3

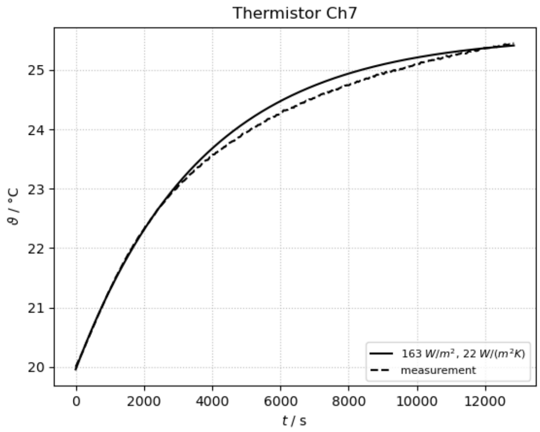

Figure 8. Comparison of measured and simulated data for thermistor at position 7.