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Originally published:

July 2018

Review of Scientific Instruments 89(2018), 073111

DOI: <https://doi.org/10.1063/1.5038423>

Perma-Link to Publication Repository of HZDR:

<https://www.hzdr.de/publications/Publ-27330>

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Advanced process-synchronized computed tomography for the investigation of periodic processes

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Abstract

Computed tomography (CT) is known for giving cross-sectional images of a body. As tomographic scans require mechanical movement of components, data acquisition is commonly too slow to capture dynamic processes, which are faster than the acquisition time for a single image. Time-averaged angle-resolved CT imaging is a more recent method, which has demonstrated a capability to sharply image fast rotating machinery components by synchronizing data acquisition with rotation. However, in this modality all information on static parts disappear. In this paper, a novel data acquisition approach is introduced that combines both CT imaging methods. Eventually, the developed method is exemplarily applied to the study of gas-liquid flow in an industrial centrifugal pump using high-resolution gamma-ray tomography imaging.

Key words

Tomographic imaging, synchronized data acquisition, multiphase flow, centrifugal pump

25 1 Introduction

26 Radiation based computed tomography (CT) is widely used for non-destructive testing, non-intrusive
27 process analyses as well as for medical diagnostics. For conventional tomographic imaging,
28 radiographic projections are acquired from different angular positions of the object of investigation
29 by either rotating a source-detector assembly around the fixed object or by rotating the object in
30 between the source and detector. Subsequently, the recorded attenuation projections are
31 reconstructed to a cross-sectional image using e.g. filtered back projection or algebraic
32 reconstruction techniques. The resulting images give the non-superimposed attenuation coefficient
33 map of the object slice or volume [1]-[3].

34 Conventional radiographic computed tomography (*convCT*) was originally developed for medical
35 diagnostics with X-rays. Here, the patient is placed between a mechanically rotating source-detector
36 assembly that continuously acquires slice images with high spatial resolution [4]-[6]. By synchronizing
37 the progressive feed of the patient through the CT scanner, so-called helical CT imaging is performed
38 providing complete volume scans of the body [7]. Furthermore, such full body CT scans are
39 meanwhile synchronized with the electrocardiogram signals from the heart's systolic and diastolic
40 phases in order to avoid motion artefacts [8]-[10]. Such synchronized CT imaging is also referred to as
41 process-synchronized computed tomography (*psCT*).

42 Meanwhile, computed tomography is an emerging technique for many industrial applications, too.
43 Non-destructive testing is often applied for quality control of technical components and materials for
44 example to detect inclusions, contact faults, fissures and cracks in integrated circuits, engines for
45 aerospace applications but also for positioning and inspection of human implants [11]-[13]. Here,
46 mainly X-ray tomography scanners have been developed and commercialized, providing images at
47 high spatial resolution of static objects. In contrast, process tomography for troubleshooting,
48 optimization and predictive maintenance in process equipment, such as chemical reactors, pumps or
49 heat exchangers relies mainly on gamma radiation [14]-[19]. Harsh process environments, process
50 dynamics, occurrence of multiphase flow as well as rotating equipment pose additional challenges
51 for reliable CT imaging with respect to dynamic imaging. So far, process tomography has been
52 applied mainly in a conventional manner providing time-averaged slice images of the material or
53 fluid phase distributions, e.g. in various chemical reactors [20]-[27]. However, information about the
54 process dynamics is often lost.

As a first step towards process-synchronized imaging, Prasser et al. (2003) introduced a novel CT imaging method called time-averaged angle-resolved CT (*tarCT*). They demonstrated the visualization of periodically changing gas fraction fields in an axial pump by synchronizing the data acquisition with the rotating parts of the pump and using an in-house developed radiation detector arc whose sampling frequency was significantly higher than the rotation frequency of the pump impeller [28]. With this approach, multiphase flows within various rotating equipment, e.g. stirred tanks [29], axial pumps [28], centrifugal pumps [32]-[34] and couplings [30]-[31], were further successfully studied. It should be mentioned that such synchronized CT data acquisition and imaging is not limited to rotating parts but can also be triggered by any kind of regular process intermittency such as periodic pulsation or flashing conditions as present for Taylor flow in capillaries [35] or for fuel injection in plunger pumps [36].

Hitherto, either *convCT* or *tarCT* have been applied exclusively for multiphase flow investigations in rotating systems. Applying both CT imaging methods simultaneously would a) reduce the CT imaging time, b) improve the reliability and interpretability of static and dynamic results if the steady state of the process cannot be guaranteed and c) provide unique data on the dynamics of multiphase flows in process equipment with periodic behavior. The latter means, static as well as periodic parts can be reconstructed sharply. Eventually, images can be compiled as a sequence, which then shows the dynamics of a process along a period of the intermittency.

In the following, a novel approach for the simultaneous imaging with *convCT* and *tarCT* is introduced, which we refer to as advanced process-synchronized CT (*advCT*). The new method has been exemplarily applied to an industrial centrifugal pump operated in single-phase and two-phase flow conditions. As CT imaging system the high-resolution gamma-ray CT scanner [14], [29] was accordingly modified and applied.

2 Materials and Methods

2.1 CT imaging techniques

In general, computed tomography can be performed with either photon integrating detectors, delivering an analogue electrical voltage signal whose amplitude is proportional to the radiation photon flux, or photon counting detectors, delivering a digital number of radiation photons that are

84 counted within a projection interval. Since the CT system used in this study operates in photon
85 counting mode, *advCT* imaging is described in the following using the count rate notation.

86 *Computed tomography* bases on the acquisition of radiographic projections of an object from
87 different angular positions. For each projection $i \in \mathbb{N} \mid 0 \leq i < N_\varphi$ the radiation intensity profile for
88 all detector elements $d \in \mathbb{N} \mid 0 \leq d < N_d$ is stored in terms of counted radiation photons in a data
89 matrix $S_{d,i}$. Thus, the count rates

$$90 \quad \dot{S}_{d,i} = S_{d,i} / \Delta t_i \quad (1)$$

91 with the sampling interval Δt_i of each projection i . A reference CT scan $\dot{S}_{d,i}^{\text{ref}}$ without object or with
92 the object in a reference state is used to calculate the radiation attenuation data matrix (sinogram)

$$93 \quad E_{d,i} = -\ln \left(\frac{\dot{S}_{d,i}}{\dot{S}_{d,i}^{\text{ref}}} \right). \quad (2)$$

94 These data are then used to reconstruct the non-superimposed slice image of the averaged
95 attenuation coefficients.

96 For *convCT imaging* the source-detector assembly (or respectively the object) is rotated with a slow
97 rotation frequency f^{CT} and provides N_φ radiographic projections during a full $0^\circ \leq \varphi < 360^\circ$
98 rotation. Accordingly, the corresponding detector sampling frequency f^{samp} is defined by

$$99 \quad f^{\text{samp}} = N_\varphi \cdot f^{\text{CT}}. \quad (3)$$

100 This way, a data matrix $\dot{S}_{d,i}^{\text{conv}}$ of dimension $N_d \times N_\varphi$ is obtained wherein stationary parts of the
101 object appear as sinusoidal structures. Thus, applying any CT reconstruction algorithm to the
102 resulting $E_{d,i}^{\text{conv}}$, static parts such as housings, baffles and nozzles are sharply reconstructed while
103 moving parts, like rotating impellers, are smeared across the imaging plane (see Figure 1a).

104 For *tarCT imaging*, the source-detector assembly is not rotated, i.e. $f^{\text{CT}} = 0$. Instead, the projection
105 data acquisition is synchronized with periodically moving (rotating) parts of the object. In case of an
106 impeller rotating with a given frequency f^{rot} , projection data are continuously sampled at a high
107 frequency f^{samp} . Accordingly, the number of projections is given by

$$108 \quad N_\alpha = f^{\text{samp}} / f^{\text{rot}}, \quad (4)$$

109 whereas f^{samp} must be significantly larger than f^{rot} . Typically, the statistics of detected photons
110 within a single projection, i.e. the number of incident radiation photons in each single detector

element, is too low. Hence, all values of each detector element of each projection angle are added over a sufficient number of cycles, e.g. impeller revolutions. Synchronization can be performed by recording the signal of any suitable revolution sensor simultaneously with the projection data. In case of a rotating impeller, a Hall effect sensor might provide a zero-crossing signal for each revolution that corresponds to an acquisition interval $\Delta t_{zc} = 1/f^{\text{rot}}$. Then, each detector reading (projection with index $j \in \mathbb{N} \mid 0 \leq j < N_\alpha$) corresponds to one angular position $\alpha_j = 2\pi j/N_\alpha$ of the impeller. Hence, the dimension of the data matrix $\hat{S}_{d,j}^{\text{tar}}$ is $N_d \times N_\alpha$.

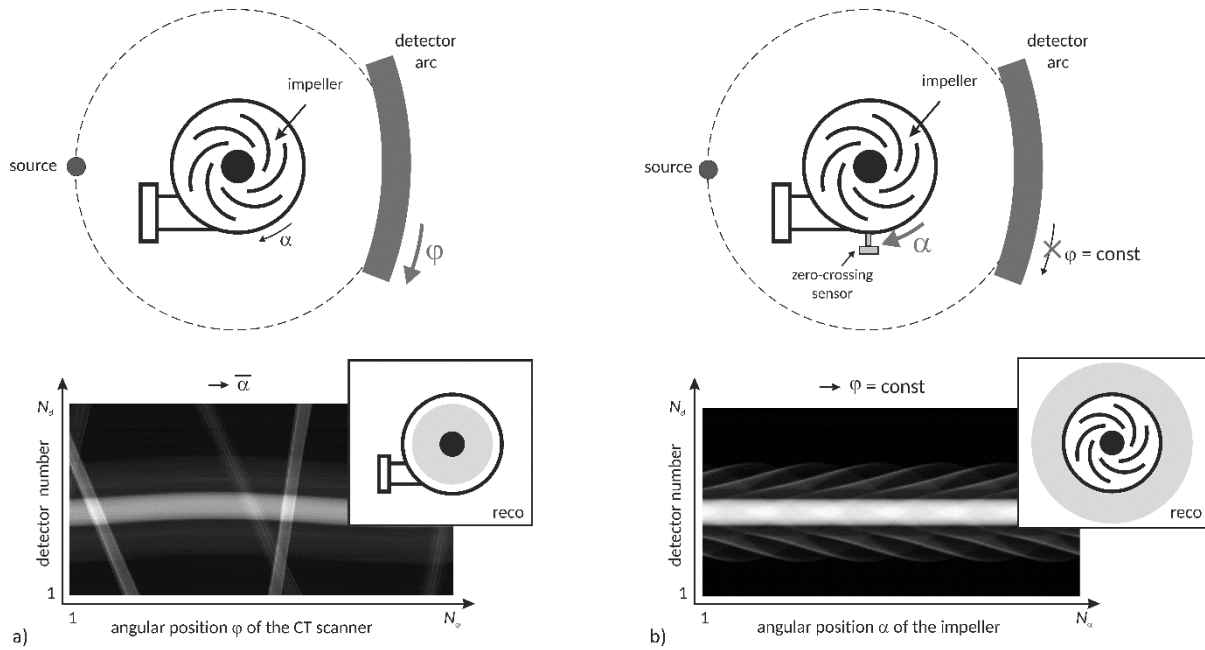


Figure 1: Scheme of setup and imaging procedure (top), obtained sinograms (bottom) and schematic view of reconstructed images (inset) with sharp (black) and angular-averaged (gray) structures exemplarily shown for a centrifugal pump applying a) *convCT* and b) *tarCT* imaging.

As mentioned above, for *tarCT* imaging projection data have to be acquired for a number of rotations N_r . Thus, a three-dimensional data matrix $S_{d,j,t}^{\text{tar}}$ is initially generated, where the index t is defined as $t \in \mathbb{N} \mid 0 \leq t < N_r$ and the index j is defined as $j = N_\alpha \Delta t_j / \Delta t_{zc}$. The interval Δt_j denotes the residual time since the last zero-crossing. By integrating over all revolutions and dividing by the total time $t_{zc} \cdot N_r / N_\alpha$ per projection angle, the count rates

$$\hat{S}_{d,j}^{\text{tar}} = \frac{1}{t_{zc} \cdot N_r / N_\alpha} \cdot \sum_{t=1}^{N_r} S_{d,j,t}^{\text{tar}} \quad (5)$$

are calculated representing radiographic projections of the rotating parts of the pump taken in the rotating frame, i.e. the impeller and all the parts including the liquid holdup rotating at the same speed (see Figure 1b).

For *advCT imaging* both previously described CT imaging methods are simultaneously performed. To obtain the sinogram data for *convCT* and *tarCT* from one measurement, a three-dimensional data matrix $\dot{S}_{d,i,j}^{\text{adv}}$ of the dimensions $N_d \times N_\varphi \times N_\alpha$ is defined at first (see Figure 2, middle). The source-detector assembly is then rotated around the object. At the first quasi-stationary projection position $i = 1, \varphi_0 = 0^\circ$ a time-averaged angle-resolved data set $\dot{S}_{d,i=1,j}^{\text{adv}} = \dot{S}_{d,j}^{\text{tar}}$ is obtained according to the procedure described above. This is repeated for each subsequent projection angle $\varphi_i = 2\pi(i-1)/N_\varphi$. After an entire rotation of the source-detector assembly $\dot{S}_{d,i,j}^{\text{adv}}$ contains N_φ sub-matrices with $i \in \mathbb{N} \mid 0 \leq i < N_\varphi$ each representing a single time-averaged angle-resolved sinogram obtained by varying the projection angle $\varphi_i = 2\pi i/N_\varphi$ of the source-detector assembly (see Figure 2, top).

Given the object to be positioned in the very center of the source-detector assembly and provided that $N_\varphi = N_\alpha$, an extended time-averaged angle-resolved sinogram

$$\dot{S}_{d,j}^{\text{tar}} = \frac{1}{N_\varphi} \cdot \sum_{i=1}^{N_\varphi} \dot{S}_{d,i,j^*}^{\text{adv}} \quad \text{with } j^* = (j - i) \bmod j \quad (6)$$

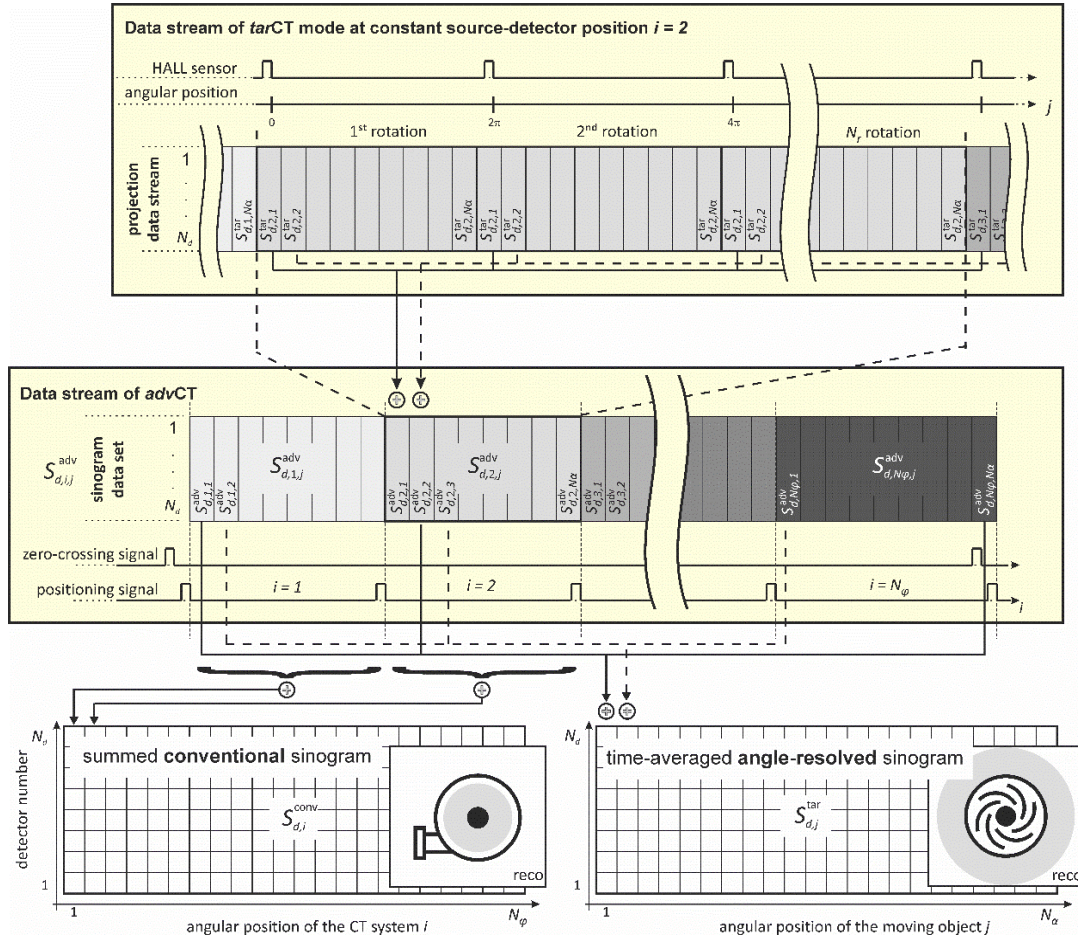
can simply be obtained by averaging shifted versions of $\dot{S}_{d,i,j}^{\text{adv}}$ containing projections with the best photon statistic. The projection shift $j^* = (j - i) \bmod j$ in $\dot{S}_{d,i,j^*}^{\text{adv}}$ compensates the angular offset between the applied *tarCT* synchronization sensor, e.g. Hall sensor, and the associated projection angle φ_i of the CT imaging system (see Figure 2, bottom, right). Averaging $\dot{S}_{d,i,j}^{\text{adv}}$ over all rotation angles j , the conventional sinogram

$$\dot{S}_{d,i}^{\text{conv}} = \frac{1}{N_\alpha} \cdot \sum_{j=1}^{N_\alpha} \dot{S}_{d,i,j}^{\text{adv}} \quad (7)$$

is obtained (see Figure 2, bottom, left).

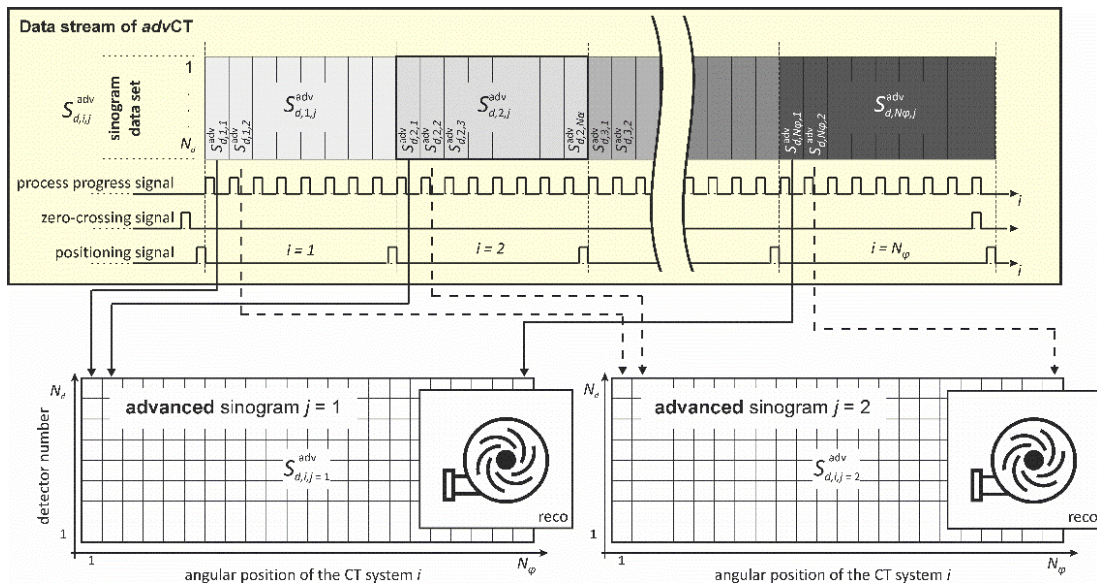
For each j the sub-matrix $\dot{S}_{d,i,j=\text{const}}^{\text{adv}}$ represents a conventional sinogram for a given (static) impeller angle position (see Figure 3). Eventually, a combined image can be reconstructed showing both the focused stationary structures as well as the rotating structures ‘frozen’ at an angular position $\alpha_j = 2\pi j/N_\alpha$. It should be mentioned, that the image is still an ensemble-average obtained over many rotations. Nevertheless, this combined CT imaging approach is practical, if structures in the object change repeatedly with the identical course for every revolution. In case of the centrifugal pump, this holds for fluid elements that enter the pump in the center and move towards the tangential outlet. Thus, such permanently occurring radial flow can be visualized with this CT imaging mode. Therefore,

160 frozen-impeller images are reconstructed for all impeller angles α . The resulting image sequence
 161 shows how ensemble-averaged structures move with the rotating impeller during one revolution.



162

163 **Figure 2:** Schematics of the projection data stream analysis to restructure projection data according to both *tarCT* and
 164 *convCT* using a data set provided by the *advCT* imaging method.



165

166 **Figure 3:** Schematics of the projection data stream analysis to restructure projections according to *advCT* for two different
 167 angular positions of the impeller, which rotates at 1480 rpm.

168 2.2 Gamma-ray CT scanner

169 The applied high-resolution gamma-ray CT scanner (HireCT) mainly comprises a collimated ^{137}Cs
170 source with an activity of about 185 GBq and a photon energy of 662 keV as well as a radiation
171 detector arc composed of $N_d = 320$ scintillation detector elements positioned opposite to the
172 source. Each detector pixel has an active area of 2 mm by 4 mm and provides a radiation detection
173 efficiency of about 75% for 662 keV gamma photons. The detector arc is focused to a distance of
174 970 mm and is operated in single photon count mode, which is very important at low photon fluxes,
175 high projection data sampling frequencies or at a combination of both. Hitherto, the HireCT was
176 operated in either *convCT* or *tarCT* imaging mode [14], [29].

177 For *convCT* imaging, the HireCT is typically rotated slowly between $f^{\text{CT}} = 0.33$ mHz (0.02 rpm) and
178 $f^{\text{CT}} = 1.67$ mHz (0.1 rpm). Accordingly, the data sampling frequency and its corresponding data
179 stream rate is rather low and hence not critical. The projection data acquisition is triggered by two
180 light barrier sensors directly mounted on the rotary stage. The first light barrier indicates the zero-
181 crossings, i.e. angular reference position. The second sensor delivers a crossing signal at every 0.36°
182 interval using a mechanically perforated ring with $N_\phi = 1000$ equidistantly distributed measuring
183 points.

184 For *tarCT* imaging, the HireCT is fixed and provides a projection data sampling frequency of up to
185 $f^{\text{samp}} = 22$ kHz, which is sufficient to sample rapidly moving parts, such as impellers of axial and
186 centrifugal pumps [33] or fluid couplings [30], [31]. Therefore, an additional very fast data acquisition
187 and transfer electronics is used and an advanced detector value read-out procedure is performed.
188 For process-synchronization, two binary status signals are connected to the electronics and are
189 directly implemented into the projection data stream.

190 To perform *advCT* imaging, the positioning information of the HireCT is recorded with the existing
191 fast data acquisition and transfer electronics. Therefore, the electrical signals of both light barrier
192 sensors were initially connected to the existing microprocessor via a dual optoelectronic coupler.
193 Further, the microprocessor firmware was modified to integrate the binary status of both light
194 barrier sensors into the existing status byte, in which already two status signals for the process
195 synchronisation sensors were coded. This way, the modified fast data acquisition electronics is able
196 to sample four external binary signals, while the size of the data stream and the data sampling
197 frequency f^{samp} is retained.

198 3. Results

199 The *advCT* imaging mode and the modified HireCT scanner are applied to an industrial centrifugal
200 pump (Etachrom BC 032-160074 C11, KSB, Germany) with a closed radial multi-vane impeller forming
201 six fluid conveying chambers. The pump was already investigated by Schäfer et al. [34] and Neumann
202 et al. [33] concerning their gas-liquid flow operation behaviour. In this study, a constant volumetric
203 gas fraction of 2.6 % is charged with the conveyed liquid (tap water). The diameter of the impeller is
204 125 mm, which rotates with a speed of $f^{\text{pump}} = 1480$ rpm. An external Hall effect sensor provides
205 the zero-crossing signals for each revolution of the pump impeller corresponding to a time interval of
206 $\Delta t_{zc} = 40.54$ ms per revolution.

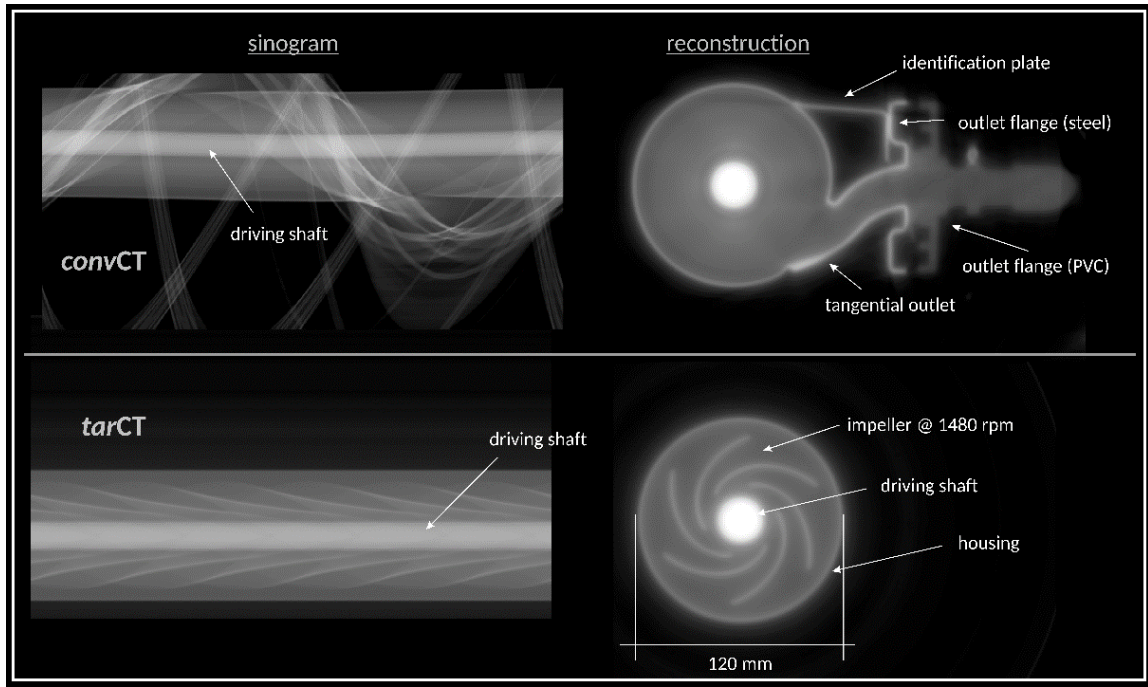
207 Eventually, *advCT* of the centrifugal pump operated with single-phase liquid and two-phase
208 gas/liquid flow are performed with a total duration of 50 min, i.e. each *tarCT* scan is performed for
209 three seconds. A single projection scan \dot{S}_d^{ref} without any object and with sufficient photon statistic is
210 used as reference for calculating the absolute radiation attenuation values. Projection data pre- and
211 post-processing are accomplished as described in Chapter 2.2 using GNU Octave v4.2.1.
212 Simultaneous iterative reconstruction technique (SIRT) was performed with 50 iteration steps on a
213 graphic processing unit by the open-source CT reconstruction tool ASTRA v1.8 [37]-[39]. Slice images
214 are reconstructed on a 1440×1440 pixel grid with a pixel size of 0.5 mm. For this purpose, the
215 obtained fan beam sinogram is resorted and interpolated to a parallel beam sinogram with virtual
216 3600 detector elements and 1800 projections for a 180° rotation.

217 As shown in Figure 4, the results of both standard CT imaging methods (*convCT* and *tarCT*) could be
218 successfully extracted from the *advCT* scan using Equations (6) and (7). It can be seen from the
219 *convCT* sinogram that the driving shaft of the impeller is not exactly positioned in the very centre of
220 the HireCT system. Thus, in addition to Equation (6), each *tarCT* sinogram $\dot{S}_{d,t=\text{const},j}^{\text{adv}}$ is slightly
221 shifted along the detector axis to achieve an overlap of the driving shaft in the final averaged *tarCT*
222 sinogram $\dot{S}_{d,j}^{\text{tar}}$. The empirically identified shifting sinus curve from the *convCT* will reduce the optimal
223 spatial resolution of the *tarCT* scan to a negligible degree.

224 Prior to reconstructing the image sequence from the *advCT*, the following additional artificial process
225 synchronisation is performed. As the impeller consists of six identical constructed and rotation-
226 symmetrically arranged chambers, each sixth part of the sinogram $\dot{S}_{d,i,j}^{\text{adv}}$ is averaged with respect to j
227 (see Figure 5) in order to significantly improve the photon statistic. Nevertheless, possible pulsations

228 of the gas phase towards the tangential outlet of the centrifugal pump are still visible in the averaged
 229 *adv*CT sinogram stack $\dot{S}_{d,i,j}^{\text{adv}}$ with $N_\alpha = N_\alpha/6$. In Figure 6, five exemplarily reconstructed cross-
 230 sectional images are shown in which the impeller is visualised in different angular positions ranging
 231 from 0° to 48° with increments of 12° (note that the 60° position coincides with the 0° position).

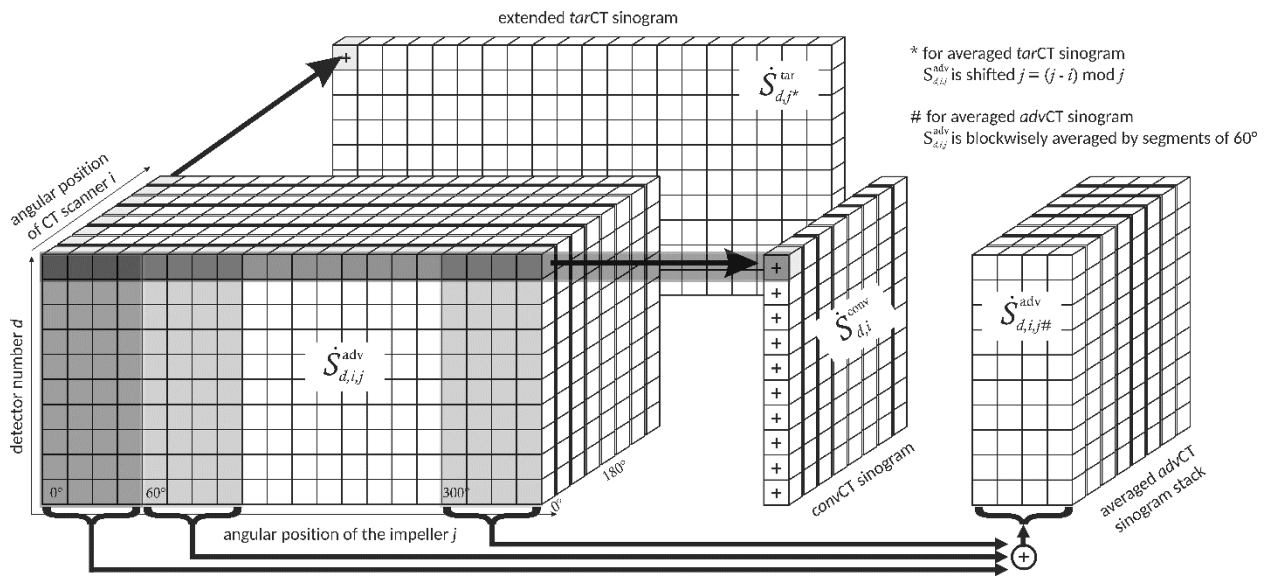
232



233

234 **Figure 4:** Comparison of *conv*CT imaging (top) and *tar*CT imaging (bottom) using the improved electronics of the HireCT for
 235 the centrifugal pump (impeller is rotating with 1480 rpm) that enables *adv*CT imaging.

236



237

238 **Figure 5:** Illustration of the data sorting procedure of the *adv*CT data stack to extract *conv*CT and *tar*CT sinograms and an
 239 averaged *adv*CT sinogram stack as well.

For the calculation of the gas fraction distributions, reconstructed absolute images of the centrifugal pump operated at two-phase flow conditions are subtracted with the images obtained from the centrifugal pump operated at single-phase liquid flow conditions and subsequently normed to the attenuation value of the liquid phase. The results are compiled in Figure 7. For a better orientation, an absolute reconstruction of the centrifugal pump is shown in the top left position.

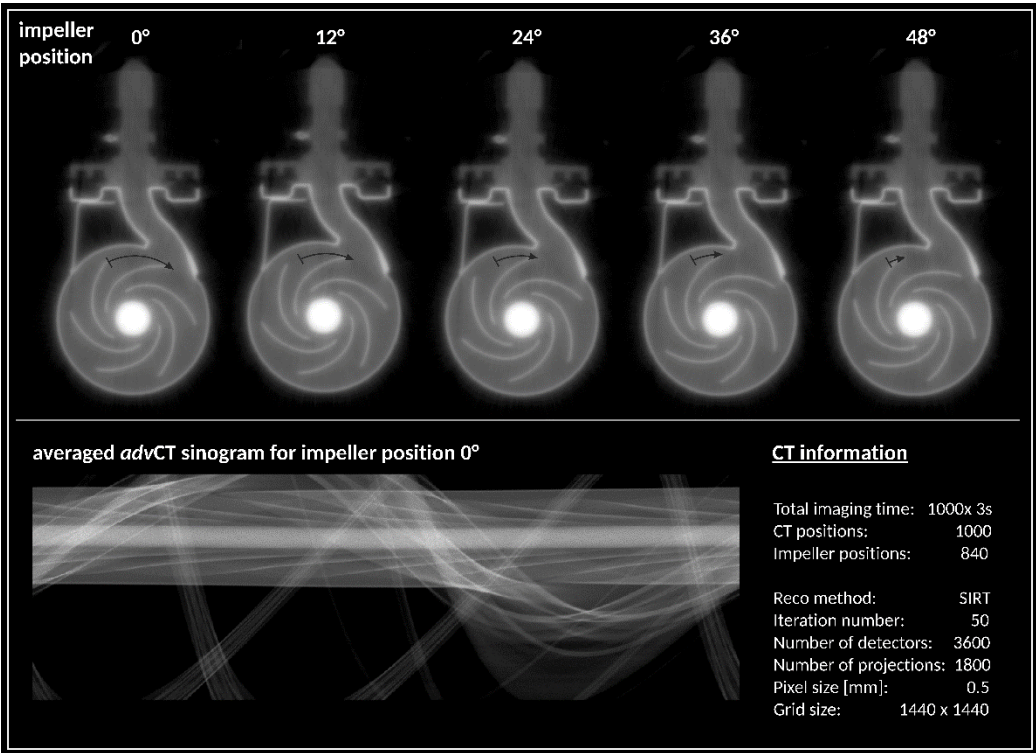


Figure 6: Reconstructions of the centrifugal pump at five different angular positons of its impeller operated at 1480 rpm.

From the averaged *convCT* imaging (Figure 7, top, centre) an asymmetric gas pocket is identified near the tangential outlet of the centrifugal pump (highlighted by the red circle), representing continuously ejected gas fraction. Furthermore, *convCT* imaging reveals a gas dead zone directly behind the tangential outlet. In contrast, the result from averaged *tarCT* imaging (Figure 7, top, right) shows no asymmetric gas phase distribution with respect to the impeller geometry. However, it can be recognized that the gas phase is homogeneously distributed in all six chambers and the gas fraction is significantly higher compared to the injected volumetric gas fraction of 2.6 %. Thus, it can be concluded that a static or dynamic gas pocket is generated within the impeller region that impedes the transport of the liquid (see also [33], [34]).

Eventually, the image sequence obtained by the averaged *adv*CT imaging procedure is visualized for selected angular positions of the impeller (Figure 7, bottom). Again gas-rich and gas-lean zones can be identified. In contrast to the averaged *tar*CT, both scenarios can now be studied in its dynamics, i.e. depending on the angular position of the impeller.

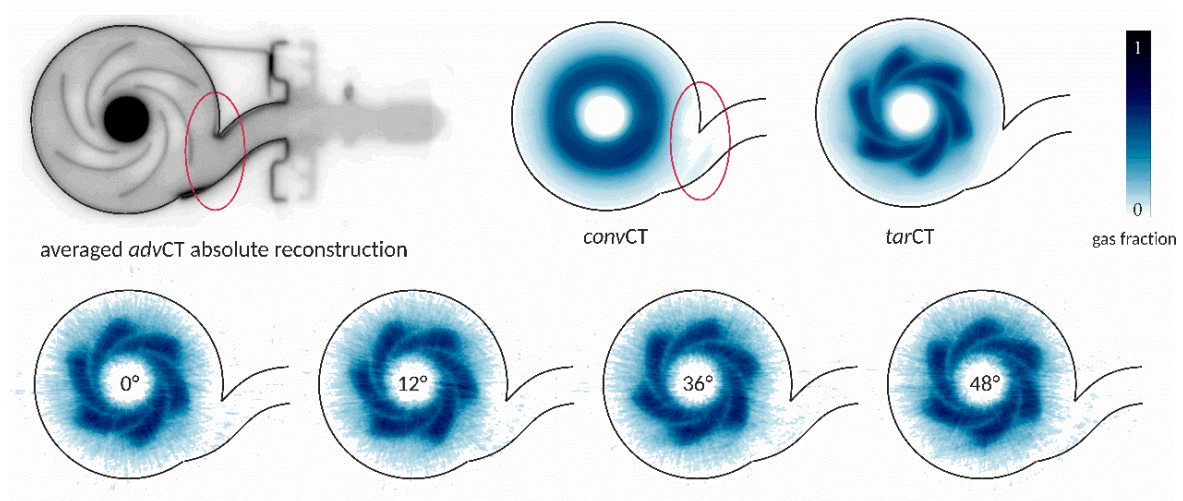


Figure 7: Visualization of the gas fraction distribution in a centrifugal pump (top, left) operated in gas-liquid two-phase flow applying *adv*CT imaging using the HireCT imaging system. Results of the *conv*CT (top, centre), the *tar*CT (top, right) and results of the averaged *adv*CT (bottom line) are shown. (Colours available in the online version)

4. Conclusion

In this paper, an advanced process-synchronized computed tomography (*adv*CT) imaging approach was presented that combines the pros of two standard CT imaging methods, namely conventional CT (*conv*CT) and time-averaged angle-resolved CT (*tar*CT). After presenting their basic principles, the *adv*CT imaging was introduced from which data of both standard CT imaging methods can be extracted. Additionally, using a new data sorting procedure, cross-sectional image sequences at different process progress stages with sharp structures of both the static and the synchronized dynamic parts were obtained. The novel *adv*CT was exemplarily proved on a centrifugal pump whose impeller rotated with 1480 rpm. Eventually, quantitative phase fraction distributions were calculated and investigated. Various static and dynamic flow processes could be clearly revealed. Thus, the amount of information was significantly increased using the novel *adv*CT imaging.

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