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Parametric modelling in industrial process tomography

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Abstract

Pixel-based tomography has been used with great success for medical applications where it is most appropriate but this approach does not always transfer easily to industrial applications. For example pixel-based image reconstruction from electrical impedance tomography measurements is well known to be an ill-posed problem and with high noise levels such tomograms cannot be reliable. An alternative approach is to use a parametric representation of the tomogram for which reconstruction can be better posed. The primary reason for parametric modelling, however, is interpretation. This paper compares parametric modelling to other methods and then gives an example of the method for an application to a hydrocyclone. Two tomographic modalities are discussed and the results from parametric modelling are validated. This example demonstrates the great power achievable from a parametric modelling approach to tomographic imaging of industrial processes. ©2000 Elsevier Science S.A. All rights reserved.

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1. Introduction

The First World Congress on Industrial Process Tomography is a clear indication of the great interest in the application of tomography to industrial processes and that such applications present new challenges for tomographers. There are different requirements in an industrial environment than there are within a medical one: different regulations regarding for example use of ionising modalities, different speed requirements. The greatest difference however is the subject matter. An industrial process might be very much simpler than the human body or indeed more complex. It is the simpler representations of some processes that allow the parametric approach outlined here and produce the subsequent advantages.

Pixel-based tomography, in which a picture is represented by an array of pixel values, has enjoyed much success in medical applications. Body scanners based upon X-rays and ionising radiation are very widely respected. The same principles can be, and have been, applied to industrial processes for many modalities. For hard fields such as ionising radiation, this approach could be equally successful in producing tomograms. Data interpretation can be a different matter. In medicine, interpretation of tomograms has traditionally been by human inspection. Industrial applications may require interpretation at very high rates analysing many tomograms per second, or require quantification for process control.

Electrical impedance tomography (where impedivity or resistivity is imaged) and electrical capacitance tomography (where relative permittivity is imaged) have now been applied to many industrial processes [1]. Linear back projection has been the favourite method of reconstruction although it is only a crude approximation. It has had speed advantages. Pixel-based reconstruction has also been advocated sometimes with an iterative method [2] that reduces speed of reconstruction. This is well known, however, to be ill conditioned and regularisation is required [3]. In the presence of high noise levels, the regularisation must be heavy and solutions produced may depend on the initial guess of the tomogram and so cannot be reliable. Some regularisation can be achieved by reducing the number of pixels but this then leads to a poorer approximation of the image [4].

The tomogram could be built upon basis functions that suit the geometry of the problem [5] or the geometry of features such as boundaries (wavelets). The weights for these functions are called parameters and their determination the parameter identification problem. In practice a subset of the basis functions will be used to reduce the number of parameters to be determined. Selecting those basis functions that best represent the expected image variations is a significant development [6].

Here it is suggested that the industrial process image be modelled to produce a parameterisation of the tomogram. A similar approach has already been partially adopted for work

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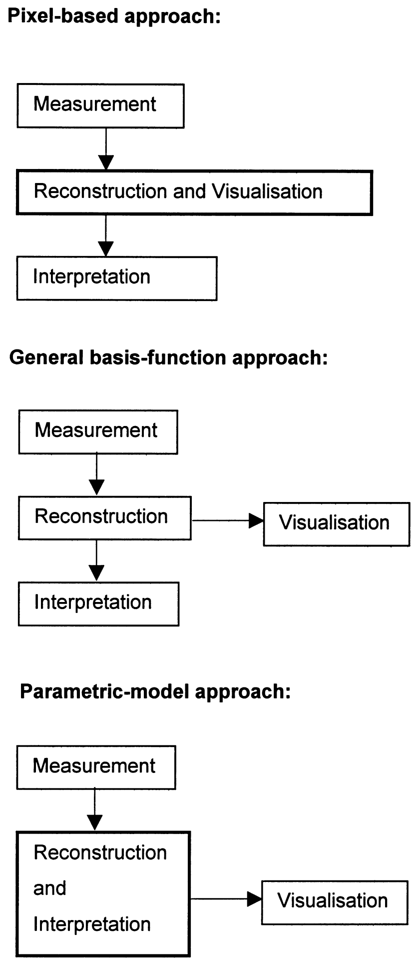

Fig. 1. Diagram to illustrate the links between units of tomography systems.

with the imaging of gas-oil flows and separation by electrical capacitance tomography [7,8] and for X-ray photography of hydrocyclones [9]. The general philosophy is to incorporate those features of the process that the tomogram is produced to elucidate. Thus, the parameters identified during reconstruction are exactly those required for image interpretation. Computational effort is thus, efficiently utilised.

If the number of parameters in the model is small then the reconstruction problem can be better posed, interpretation is efficiently accomplished and a suitable quantification is made available for process control purposes. This is viewed as a complete philosophy of process measurement, presentation, and control.

Fig. 1 illustrates the differences in the approaches outlined above. In the pixel-based approach, there is a direct link between the tomogram representation and the display of the tomogram. Often interpretation is from a displayed tomogram (as in medical applications) but this is not practical for automated process control, especially if tomograms are to be interpreted at a rate of many per second. For soft-field tomography, data is linked to a tomogram by a reconstruction algorithm by a complex relationship. Only for a parametric model based tomogram is there a direct link between the tomogram and interpretation.

In Section 2, an example is given of the application of parametric modelling to a hydrocyclone. The method is described for two different modalities: reflection-mode ultrasound tomography (UST) and electrical resistance tomography (ERT).

It is important to observe that a poor model could yield poor results. Hence, it is necessary to have adequate background to the industrial process which is to be studied. Parametric modelling and fitting can then provide better detail.

Note that there is always a model: the model might be that the image comprises pixels. Here the philosophy is to find a better model than pixels; one that aids interpretation and is able, due to better posing, to gain more from the measurements.

In the hydrocyclone example which follows, great care has been taken in the analysis of the results and validation sought by the use of three different imaging modalities. A more detailed model would contain more parameters but then it would not be practical to determine these well. The best model describes the industrial process and what interpretation is sought whilst being parsimonious so that reconstruction (parameter determination) does not become ill posed or ill conditioned.

2. Hydrocyclone imaging

The fluid-dynamic modelling of high-density slurries within a hydrocyclone remains a very complex problem. A body of work has been undertaken bringing together a number of tomographic modalities in order to image within the cyclone [10]. The results from this can then be used to verify fluid dynamics work and phenomenological models [11,12]. Performance can also be seen directly and related directly to image features such as the air-core diameter.

It is possible to proceed with pixel-based images. The aim of the project is to extract image features, and compare and combine the results from the different modalities. Thus, the features provide the link between modalities rather than pixels. Note also that pixel-based images are not straightforward to compare, since each modality might use a different pixellisation, and the reliability and accuracy of pixel values might vary within each tomogram as well as between tomograms.

Ultrasound tomography was also employed with 16 transducers mounted in a ring to image a plane close to the top of the hydrocyclone. Reflections from the air/liquid interface at the air-core boundary are used to identify the air-core location. A typical pixel-based image is shown in Fig. 2.

Darker pixels indicate that a reflective interface is more likely within the pixel. The location, size, and shape of the air-core can be clearly seen: it is a circular object at the centre of the hydrocyclone.

Fig. 2. Pixellated reflection-mode ultrasound tomogram of a hydrocyclone.

A search for circles within such a pixellated tomogram using a Hough transform has been detailed in [13]. It is perhaps simpler, however, to directly fit a circular air-core model. A circular air core of a given radius can be judged as regards to its suitability by a measure of the goodness of fit between the observed times of flight and those calculated from theory (Fig. 3). In this way an image of the air core can be achieved without any reference to pixels.

Electrical resistance tomography was also applied to the hydrocyclone in eight planes throughout the hydrocyclone body. To facilitate comparison, some experiments were undertaken using brine only. For these it is clear that the circular air-core model is again appropriate. The conductivity of the brine is known and air can be assumed non-conducting. Imaging is, therefore, simply a matter of determining the position (two parameters) and the radius (one parameter) of the air core. The image is simple and adequately describes the process as it might be judged by the sensor system. If the air core does not have a circular cross section, the ERT measurements will be unable to distinguish the departure from the circular model without extreme precision, which is not available. This is an important modelling issue.

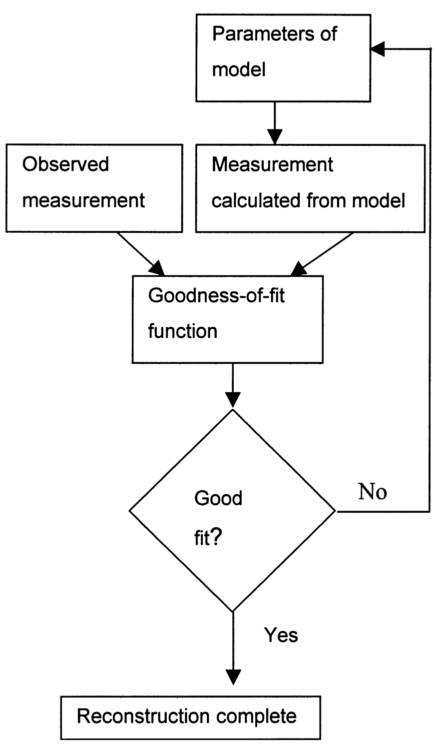

Fig. 3. Diagram to show reconstruction procedure for parametric model.

Reconstruction of the image/tomogram is also very simple. For a given state defined by a set of parameter values, a goodness-of-fit measure can be (as shown in Fig. 3) defined to compare the observed voltages with those calculated by electric-field calculations. Fitting can then proceed as in Fig. 3.

From the many experiments undertaken using brine and mineral slurries, it was soon determined that the air core appeared very close to the centre of the hydrocyclone. The maximum deviation was in the upper plane and did not exceed 2% of the diameter of the vessel. This may have been influenced by the rate of data capture since a slow collection protocol was followed to minimise noise levels. Note again that deviation from the model of a central air core is at the limit of the data accuracy in these experiments. Under this assumption with brine only, there is a single parameter to be determined that appropriately summarises the cross-sectional image.

For experiments with slurry, it is known that conductivity will vary with the concentration of the slurry within the hydrocyclone separator. Indeed this phenomenon is of primary interest in the study of cyclones. From the above discussion concerning a central air core and the speed and accuracy of measurements, it is natural to assume axial symmetry (rotational invariance) within the cyclone. Thus, a one-dimensional radial conductivity profile is sought. The central part of this will comprise an interval of zero conductivity corresponding to the air core.

Note that should the assumption of axial symmetry be inappropriate, then the fit to the measurements would be poor: large discrepancies would be seen between the observed measurements and those predicted by the model. This was certainly not the case for this campaign of experiments.

Each of the eight planes was initially treated as a single unit from which a tomogram was determined. An adjacent measurement protocol was undertaken using the 16 equally spaced and equally sized electrodes giving 104 measurements. With the assumption of axial symmetry, there are seven different measurements, six repeated 16 times each and one repeated eight times. These were taken in a noisy industrial environment at a processing plant. Under these circumstances, it was decided that the conductivity profile within the slurry be modelled with a quadratic function requiring three parameters. For efficiency the following form, with orthogonal components, was used:

$$\sigma(r) = a + b(3r - 2) + c(10r^2 - 12r + 3)$$

where σ is conductivity, a,b,c are parameters and r is the position between the air core and the boundary such that 0 corresponds to the air-core boundary and 1 to the wall of the hydrocyclone.

Given a specific state of the system defined by the four parameters (air-core radius plus the terms a,b,c of the quadratic), then the expected voltages can be determined by numerical solution of the electric-field equations. The best fit to the measurements can be calculated, given a suitable goodness-of-fit measure. Often a least-squares metric is used, but care should be taken over the selection. Many optimisation routines could then be used to find the parameters that give the best fit. A quasi-Newton scheme might be chosen for efficiency [14], or a Metropolis scheme [15] if the solution space is to be explored (in general, multiple local optima can be present).

A typical stacked tomogram reconstructed by this parametric-modelling approach is given in Fig. 4a. The tomogram reconstructed from the same data by linear back projection (LBP) is shown in Fig. 4b. In each case, eight imaged planes are displayed where the sizes and positions are as the cross sections in the conical cyclone body.

Discussion of the two methods is given in the Section 4. Note, however, that the parametric model gives far better detail, not only of the air core, but also of the distribution of solids. That is the parametric model yields the features of interest as it was designed to do. Regions of low conductivity/high solids can be seen near the cyclone wall close to the spigot and around the vortex finder (centre of the largest plane). This is consistent with computational-fluid-dynamic modelling of hydrocyclones.

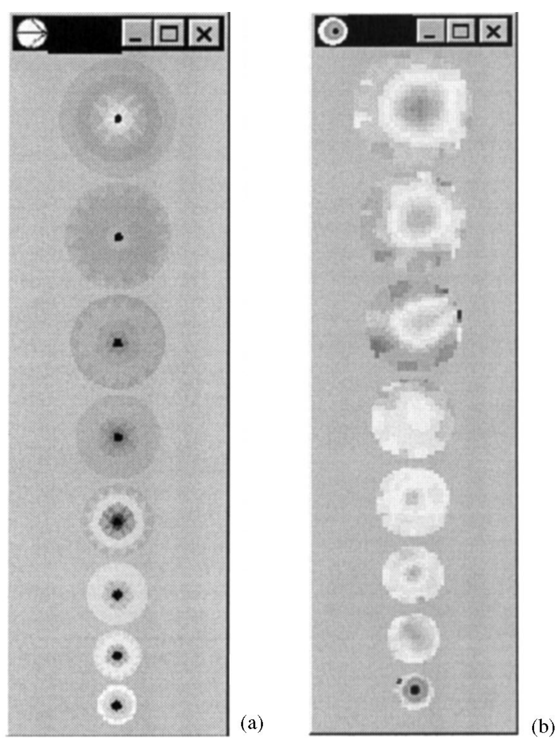

Fig. 4. (a): Tomogram of a hydrocyclone reconstructed by parametric modelling. The central air core and details of solids distribution can be seen. (b): Tomogram reconstructed using LBP from the same ERT voltage data as in (a).

The air-core and solids-variation features do have some influence on the LBP tomogram but are not clearly discernible. Can the parametric model provide better information? The next section documents some of the work undertaken to validate the claims.

The results obtained from the hydrocyclone experiments and on-line monitoring have been very encouraging. The air-core size is precisely determined and the solids distribution throughout the cyclone is mapped. The great advantages of these are discussed elsewhere [10].

3. Validation

The assumption of axial symmetry, which was found appropriate, removes the requirement of multiple projection in X-ray tomography. Consequently a hydrocyclone rig was taken to an X-ray cell for X-ray photography. Numerous experiments were undertaken with short exposure times in order to assist detection of temporal variation. Motion of the air core was again at or below the accuracy limits of the camera but the multiple X-ray photographs can be combined to yield less noisy pictures. The output from the camera was again in the form of pixellated images. The air core can be clearly seen in a typical photograph shown in Fig. 5.

Detail of variation in slurry density can be extracted from the image [16] but in relation to a single pixel the result, even after averaging many pictures, would be dominated by

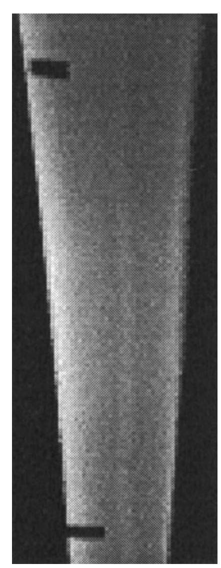

Fig. 5. X-ray photograph showing central air core. The dark rectangles are markers.

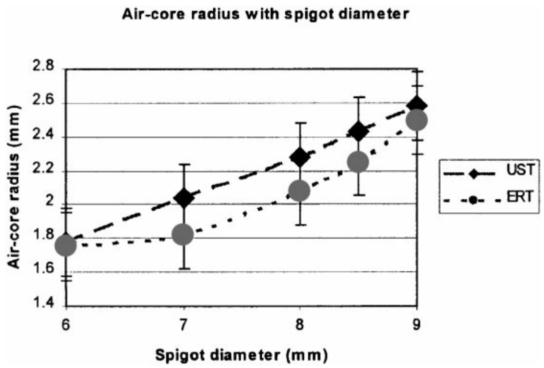

Fig. 6. Graph showing agreement within 10%, and certainly within tolerance, of air-core radius determination by two separate tomographic modalities: UST and ERT.

noise. To get useful information, pixels might be grouped. A better approach, which has been adopted by others [8], is to fit a parametric model to the radial solids concentration. Fitting can again be achieved by determining the best fit to the observed X-ray pixel intensities after correction for distortion and aberration of the camera and the geometry of the vessel (conical). That is the modelling and fitting procedure followed (and shown in Fig. 4) can be the same whatever the modality. This has advantages for data fusion, covered in another paper [17].

Note that it is now an easy matter to compare results from the three modalities since a common parameter, the air-core radius, is used.

For water only, the air-core radius determined by UST, ERT, and X-ray have been in close agreement (all around 2 mm). When the spigot diameter varies the air-core size changes a small amount. The change is detected by both UST and ERT. These modalities report similar sizes and trend: the air core varies linearly from 1.8 to 2.5 mm as shown in Fig. 6. Smaller variations occur with pressure change.

Note that although all the ERT values are slightly less than the UST values, with only five matched pairs this occurrence is not unlikely (not significant for example using a sign test): there is insufficient evidence to indicate any systematic error. The main result is that two very different tomographic modalities yield almost identical values.

Sufficiently accurate determinations have not yet been achieved from the noisy X-ray data but are expected also to closely agree. For mineral slurries, the UST data has yet to be processed, but again close agreement was seen between ERT and X-ray predictions of air-core radius. Concentration profiles have so far only been calculated from ERT measurements.

4. Reconstruction of soft-field tomograms

The reconstruction of tomograms for soft-fields as in ERT and electrical capacitance tomography (ECT) is not straightforward. It is, in the technical sense, an inverse problem. Pixel-based reconstruction can be achieved but only after much work and drastic approximations. Most commonly, a linearisation of the problem is undertaken which imposes great restrictions [4]:

1. It is assumed that there are no large changes in the conductivity (ERT)/permittivity (ECT) field. Note that for the hydrocyclone, the air core does have a drastically different conductivity–it does not conduct.
2. It is assumed that spatial variation is slow: that there are no discontinuities for example in the conductivity/permittivity fields. In the hydrocyclone there is a discontinuity at the air core.

Further false assumptions are made in order to reconstruct by linear back projection. This last, however, is a very popular method because it is fast and simple. Note that blurring and anomalies then proliferate and the second restriction results in very low spatial resolution.

When the above linearised schemes are iterated, seeking to optimise the fit of the many parameters, multiple local optima are often encountered. This is a further problem that is not easy to overcome in an automated scheme. Reconstruction time is also greatly increased and is not acceptable for processes that have rapid dynamics.

The parametric-model approach outlined in previous sections has the advantage of using far fewer parameters. This makes optimisation much faster and the inverse problem can be better posed (restricting the number of parameters has a substantial regularising effect). When the ratio of parameters to measurements is reduced, the occurrence of multiple local optima is less often encountered.

5. Conclusions

The philosophy of parametric modelling in tomography has been presented and compared to other approaches. An example was given to show how reconstruction and interpretation are combined with this approach. The variables from the model were used as an accurate and appropriate summary of the tomograms. These variables are thus, suitable for controlling the hydrocyclone slurry-separation process: determining best operating conditions and monitoring fault conditions.

For soft fields, linearised pixel-based schemes have serious restrictions that can make them unsuitable for some industrial applications (of which the hydrocyclone application is one). The parametric modelling procedure given can be better posed, and it avoids linearisation with its subsequent restrictions.

When multiple tomographic modalities are applied to the same process, there is great advantage in using a common model for all modalities. This enables comparison of the resulting tomograms so that for example relative performance of the modalities can be assessed.

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