Speckle imaging of circuit breaker arcs—toward tomographic imaging

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Gas circuit breakers play an important role in high voltage electric power transmission networks; one of their most important functions is to interrupt the short-circuit currents that flow in the case of a fault in the system. An imposed, axial, transonic gas flow is used to cool, and ultimately interrupt the arc. Understanding the interaction between this gas flow and the arc, especially during the crucial phase of current interruption that occurs around the zero-crossing of the alternating current, is key to improving circuit breaker performance. Integral quantities—such as the current and the arc voltage—can readily be measured, but they provide limited and indirect information. Recently, we have shown that speckle imaging can be used to obtain spatially resolved information about the density, temperature, and conductivity of the arc and surrounding flow via measurement of the gradient of the refractive index. A key limitation of speckle imaging with a single probe beam is that it only provides accurate results if the arc and surrounding flow exhibit axial symmetry, a condition not always met by circuit breaker arcs. Speckle tomography—the use of multiple probe beams at different angles—overcomes this limitation. In this work, we demonstrate a modular approach to extending Speckle imaging to multiple probe beams and estimate the number of probe beams needed for an accurate reconstruction of the major features of the arc and surrounding flow.

1. Introduction

High voltage circuit breakers are used in the electric power transmission network to switch the current flowing through individual power lines or other elements of the network on and off during normal operation. They are also designed rapidly to interrupt short circuit currents that flow when a fault occurs in the network. In high voltage networks, gas circuit breaker technology primarily is employed. A gas circuit breaker operates by separating two contacts in a gaseous medium—overwhelmingly, pressurized SF_6 is used in equipment sold today—resulting in an arc being drawn between them. In some circuit breakers, the energy in the arc is used to build up pressure in an intermediate volume. In addition, a piston is always used to build up pressure mechanically. The stored pressure is released into the arc zone when the alternating current approaches a zero-crossing, resulting in a transonic gas flow that passes through a nozzle system arranged around the contacts so that it axially cools and ultimately extinguishes the arc. The key to improving circuit breaker performance—to enable higher voltage and current ratings to be achieved with the same or lower mechanical drive energy in more compact equipment—is a detailed understanding of the interaction between the arc and the surrounding gas flow that leads to arc interruption at a zero-crossing of the current.

In typical investigations of circuit breakers, the current, the arc voltage, and the pressure at specific locations are measured; refer, for example, to [1]. The current measured several hundred nanoseconds before the zero-crossing can provide information about whether the interruption process will be successful or not [2]. However, these measurements do not provide the necessary physical insight into the interruption process. In order to understand the interaction between the arc and the surrounding gas flow, researchers turn to computational fluid dynamics (CFD) simulations [3]. However, given the complexity of these models and the absence of experimental data to verify the spatially resolved distributions of key parameters they predict—such as the density, temperature, and conductivity—it is difficult to assess their accuracy. Recently, we have applied Speckle imaging to measuring the spatially resolved refractive index distribution in an arc embedded in a transonic flow [4]. The measured refractive index can in turn be used to derive information about the density, temperature, and conductivity distributions. Speckle imaging yields a projection of the refractive index distribution onto a plane normal to the propagation direction of the probing laser beam. The three-dimensional distribution can be reconstructed accurately only if it is axially symmetric. Otherwise, a tomographic approach with multiple probe beams is required. Since the arc and surrounding flow between the contacts of a circuit breaker can become unstable, axial symmetry can often not be assumed. The applicability of the Speckle imaging technique can thus be greatly extended by using a tomographic approach.

In this work, we present a modular approach to setting up a multiple probe beam experimental setup and demonstrate this with a second beam-line. The analytical techniques applied to single probe beam Speckle imaging are extended to an arbitrary number of probe beams. Finally, we present estimates of the minimum number of probe beams needed to resolve the main features of an arc embedded in a gas flow.

2. Experimental setup

The experimental setup used to perform Speckle imaging with a single probe beam was presented in detail in an earlier paper [4]. Briefly, a 532 nm nanosecond pulsed Nd:YAG laser beam (Crystalaser CRL-QL532-100-YG) was expanded and passed through the arc zone of a model circuit breaker. Here, we focus on measurements that were performed at the nozzle exit (which is directly accessible to optical measurements); measurements in other locations are possible with the appropriate placement of windows. The laser beam was then passed through a glass diffuser (offset by a displacement distance from the object plane of the imaging optics), which generated a Speckle pattern that was recorded using a camera sensor. The cross-correlation of two Speckle patterns—one recorded with the arc and gas flow present and the other without—yields information about the refractive index integrated along the line-of-sight of the laser beam.

Efficient and cost-effective extension of the experimental setup to multiple probe beams was achieved by mounting the optical equipment (both on the laser and on the camera side) on a sturdy, mobile frame built out of aluminum profiles. Optical breadboards could easily be fixed to the profiles. An optical cage system mounted on the breadboards was used to permit easy alignment and centering of the optics and measurement of the distances between optical elements. In principle, the number of probe beams (or, equivalently, angles from which images can be obtained) is only limited by the space available for optical breadboards. To demonstrate this approach, a second probe beam was installed at a 90° angle to the first by splitting the laser beam using a non-polarizing 50:50 cube beam-splitter. The construction of the second probe beam was otherwise identical to the first. The two beam-lines can be seen in Figure 1.

The current and gas flow in the test device were triggered in the same way as detailed in previous work [4]; an ignition wire was used to start the flow of current. An Agilent 33522B function generator was used to coordinate the timing of the two monochrome scientific cameras (Prosilica GT4905 and GT2300) and a single laser pulse. It is important to note that both cameras have the same intrinsic trigger delay since they use the same trigger electronics, which simplifies correct synchronization.

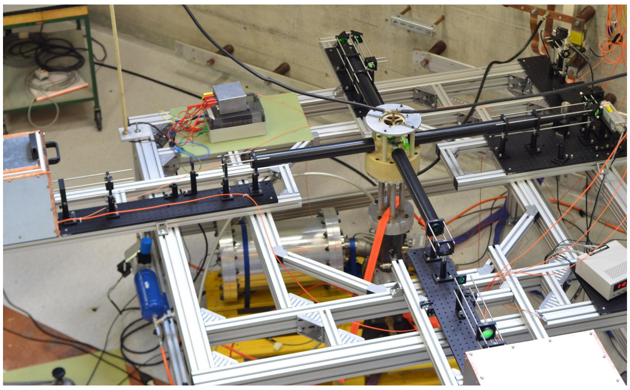

Figure 1. Photograph of the experimental setup showing the two identical beam-lines.

A current with a frequency of roughly 20 Hz and an amplitude between 1 and 2 kA was used to ensure that no gas flowed prior to arc ignition (this could otherwise remove the ignition wire before the start of current flow), and that steady gas flow had been established at the time of the current-zero crossing. A spark gap in a second LC circuit was triggered just prior to the current-zero crossing in order to inject a 500 Hz oscillation with a well-defined, precisely controllable current slope prior to current-zero. Speckle images were acquired at the current-zero crossing.

The approach described here can readily be extended to additional beams. It is important to note that it is more cost-effective to purchase a single high energy pulsed laser and to split the beam than to purchase multiple lower energy lasers. However, splitting a single beam into multiple beams using conventional beam-splitter cubes is cumbersome and makes alignment difficult (a change in the alignment of a single beam path may require re-alignment of multiple additional beams). To overcome this problem, it is possible to use fiber beam-splitters; the beam is coupled into a single fiber, which is split into a large number of fibers. Each fiber can be used to provide laser illumination for a single probe beam.

2. Image processing

The image processing algorithms used to convert the reference image and the image with arc and gas flow for each probe beam into the line-of-sight integrated refractive index change were described previously [4]. The line-of-sight integrated refractive index change simply represents the projection of the three-dimensional index of refraction distribution onto a plane perpendicular to the propagation direction of the probe beam.

The three-dimensional refractive index change distribution can be re-constructed from multiple projections using the Radon transformation. Two different approaches were used to re-construct the three dimensional refractive index change distribution. The first approach simply used the well-known filtered back-projection algorithm implemented in Matlab (The Mathworks, Natick, MA, USA). The second approach relied on a modified (to take into account negative values of the change in refractive index) maximum likelihood estimator method (MLEM) that has been shown to provide better results in certain cases [5] (and references therein). In the former case, the input data were provided in one degree steps; angles from 0 to 90° were set to the result of the first probe beam, and angles from 90 to 180° were set to the result of the second probe beam. The three dimensional refractive index distribution was calculated from the three dimensional refractive index change distribution by taking advantage of the fact that the refractive index outside of the flow in ambient air is well known.

3. Results

An example of the refractive index distribution obtained with the MLEM method of performing the Radon inversion is given in Figure 2. The refractive index data can be converted into density using tabulated information about the dependence of the refractive index on density and pressure [4]. The pressure was estimated by assuming that the pressure distribution measured in the absence of an arc using Speckle imaging does not differ greatly from that in the presence of an arc. The resulting density distribution is illustrated in Figure 3. The decaying arc channel imaged is not well-resolved by the tomographic re-construction. While a density close to 0 kg/m^3 is expected in the region of the arc (around x = 0 mm) where very hot gas is present (> 5000 K), the re-constructed density does not dip below roughly 0.5 kg/m^3. This indicates that a tomographic re-construction with only two beams is not insufficient—a result that is not unexpected. In fact, by symmetrizing a single projection (refer to [4] for details) a more physical re-construction can be obtained. Clearly, additional beams are needed to successfully re-construct the density distribution of an axially blown arc near current-zero.

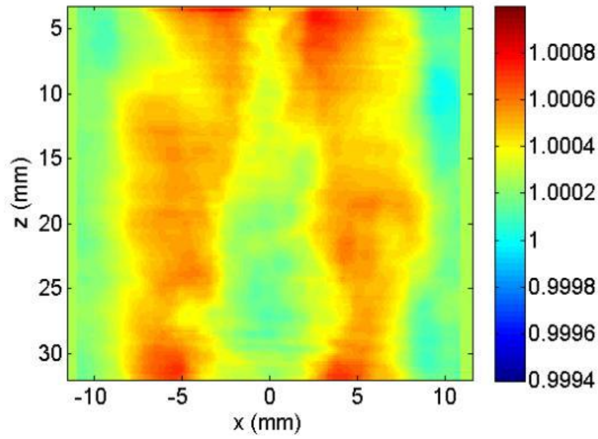

Figure 2. Refractive index distribution re-constructed from two Speckle projections of the arc at 90° to each other. Note that z = 0 corresponds to the position of the nozzle exit and that downstream distance increases with z.

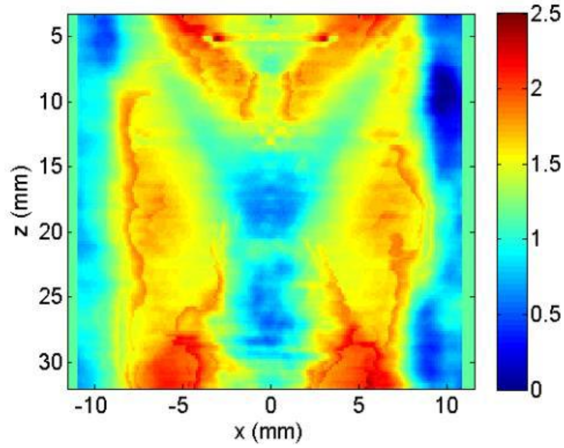

Figure 3. Density distribution calculated from the refractive index distribution shown in Figure 2.

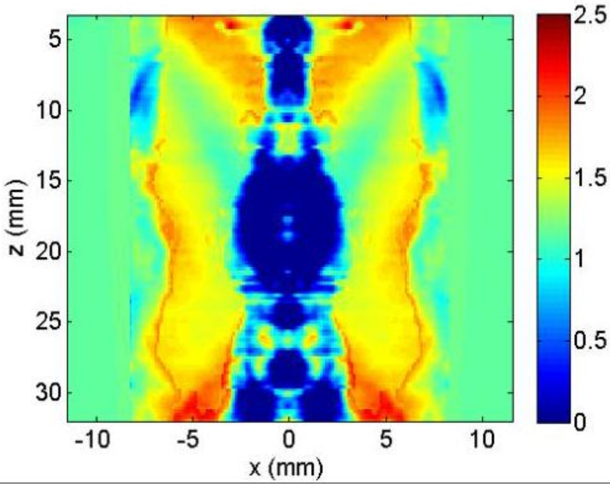

Figure 4. Density distribution re-constructed from a single Speckle projection of the arc (after it was symmetrized). Compare to the re-construction with two beams presented in Figure 3.

3. Theoretical estimates

An important parameter that must be determined before an effective Speckle tomography setup can be designed and built is the number of beams needed to resolve the key three-dimensional features of the arc and the surrounding flow. To address this, calculations were performed with Matlab using the standard Schepp-Logan phantom with a negative offset of 0.1 to take into account that the change in refractive index can be negative [5]. Both filtered back projection and the modified MLEM method were used. The Schepp-Logan phantom is illustrated in Figure 5. The re-construction (together with the original image data) along the vertical line indicated in Figure 5 is shown in Figure 6. A similar plot is shown for the horizontal line in Figure 7. Roughly eight probe beams (or, equivalently, angular steps) are needed to adequately re-construct the large-scale features of the Schepp-Logan phantom. It can be expected that a roughly similar number of probe beams will be required to re-construct the three-dimensional features of an arc embedded in an axial gas flow. Under conditions with particularly high symmetry, fewer probe beams may suffice.

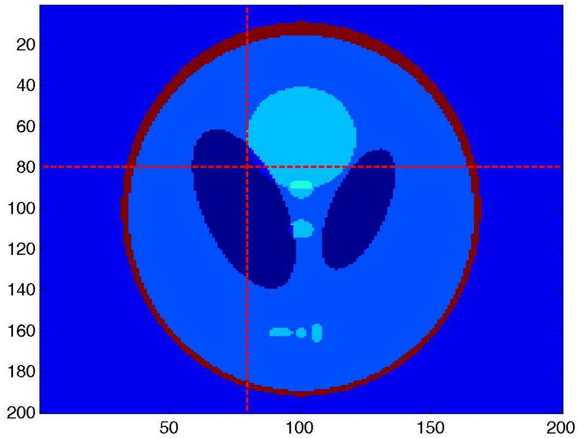

Figure 5. Shepp-Logan phantom used to study the influence of the number of projection on the quality of a tomographic re-construction. The re-constructions along the vertical line are shown in Figure 6; the re-constructions along the horizontal line in Figure 7.

4. Conclusion

We have presented a modular and efficient approach to extend Speckle imaging using a single probe laser beam to tomographic re-construction with multiple probe beams. Extension to a second beam has been demonstrated, and we have shown that the addition of further probe beams is straightforward. Theoretical estimates suggest that a minimum of roughly eight beams is needed for an adequate re-construction of large-scale features.

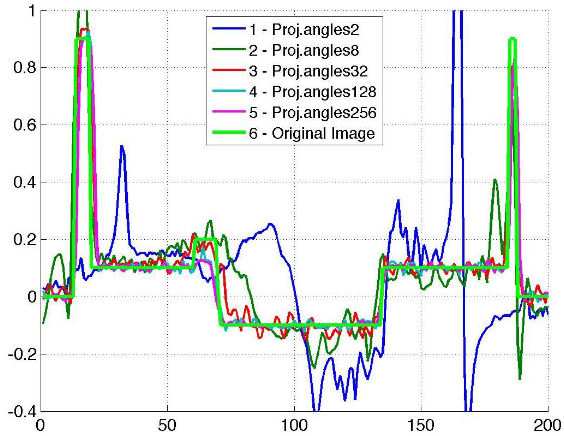

Figure 6. One-dimensional cut through the Schepp-Logan phantom (Figure 5) along the vertical dashed line reconstructed using filtered back projection.

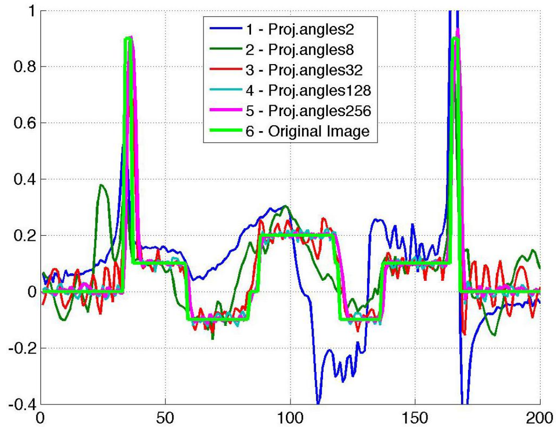

Figure 7. One-dimensional cut through the Schepp-Logan phantom (Figure 5) along the vertical dashed line reconstructed using filtered back projection.

5. References

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