Phase retrieval for improved multi-dimensional velocimetric analysis of X-ray blood flow speckle patterns

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ABSTRACT

Three-dimensional flow measurements, obtained from high-resolution synchrotron-based x-ray phase contrast images of blood *in-vitro*, are presented. Using data collected on beamline BL20XU at the SPring-8 synchrotron in Hyogo, Japan, we demonstrate the benefits to be gained by pre-processing of speckled X-ray phase contrast images prior to PIV analysis. Such pre-processing techniques include use of a Fourier mask filter to remove various beam artefacts and the application of a simple single-image phase-retrieval algorithm [1]. Whilst the cross-correlation peaks calculated from a dynamic speckle pattern exhibit oscillations characteristic of propagation-based contrast, use of phase retrieval removes these effects to yield a peak that represents the probability-density function [2] of the flow rates within the measurement volume. From this may be derived the average velocity. If the sample exhibits axi-symmetric flow geometry, such as the cylindrical capillary tube used here, then this average may be further integrated and the full radial profile may be tomographically reconstructed through use of the inverse Abel transform. In this way, a three-dimensional velocity field may be measured from a single-image sequence.

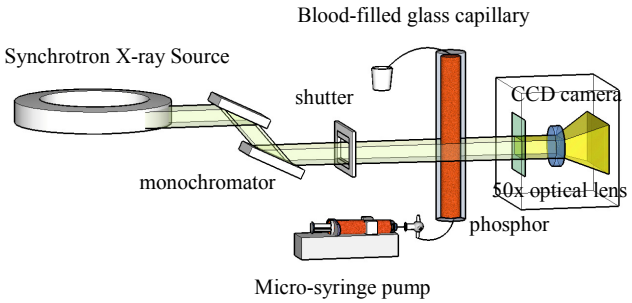

Figure 1. Schematic of x-ray phase-contrast PIV experiment.

1. INTRODUCTION

The importance of high-resolution *in-vivo* blood flow measurements is highlighted by the link between hemodynamics and cardiovascular diseases such as atherosclerosis [3]. Currently multi-dimensional velocity field measurements of blood are mainly limited to ultra-sound Doppler effects, which suffer from poor spatial resolution [4].

However the past few years have demonstrated considerable promise [2, 5, 6] in the technique of X-ray Particle Image Velocimetry (X-ray PIV), a variant of the more traditional PIV which does not require optical transparency of the sample.

X-ray PIV, which to date has been demonstrated only with blood flow that is *in-vitro*, works through the application of propagation-based phase contrast imaging. The x-ray wavefield propagating through the sample is not only weakly attenuated (the mechanism by which image contrast in conventional radiography is achieved); it is refracted or scattered also. The wavefield accumulates small phase variations dependent on the sample shape and constituent materials. Once the wavefield is allowed to propagate some distance (achieved simply by moving the detector backwards) these phase differences in the wavefield will self-interfere, producing intensity variations which can be measured [7]. Several important advances in the field of X-ray PIV have been made via the study of metallic microparticles seeded within a glycerin fluid mix [2, 8]. In the case of blood, which is composed of high numbers of weakly scattering red blood cells (an adult male has a typical hematocrit, or volume density of 45%), the result is a characteristic dynamic speckle pattern [6, 9]. Thus it is possible to measure flow even without the addition of tracer particles.

To be successful, X-ray blood PIV requires state-of-the-art equipment. Synchrotron X-ray sources provide tuneable, brilliant and partially coherent radiation. The very high achievable flux is necessary to be used in conjunction with ultra-fast detectors which capture the changing speckle at high resolution (~2μm) and with millisecond exposures.

The usefulness of phase contrast imaging systems for extracting both quantitative and qualitative sample information is well established, particularly in bio-medical applications (see, for example, the review article in [10]). Here, we demonstrate the benefits to be gained by the application of a simple phase retrieval algorithm to the speckled propagation-based phase contrast images used for X-ray PIV analysis. The improved correlation-peak forms reveal information over the entire depth which is then used to tomographically reconstruct the radially varying velocity profile. Contrary to particle *tracking* velocimetric (PTV) techniques, which require the ability to individually identify particles in at least two imaging frames, this statistically robust 3-Dimensional measurement is applicable with no upper particle limit.

2. EXPERIMENTS

The *in-vitro* experiment was conducted on the 20XU undulator beamline at SPring-8 synchrotron, Japan. We worked at the upstream hutch, located 80m from the source (~10^{13} photons/mm/sec). A schematic representation of the experimental configuration is shown in Fig. 1. X-ray energies of 25keV were selected with a Si-111 monochromator. The sample was a cylindrical glass capillary of 570µm inner diameter and 200µm wall thickness, through which a blood mixture was pumped by a Harvard micro-syringe pump system. Maximum visibility of speckle was achieved at a sample-to-detector propagation distance of 38cm.

We used whole blood, where gravity-separated plasma was replaced with an equal amount of sugar solution, in order to reduce the mass-density difference of the cells such that sinking was not a problem in low-velocity flows. A 50X magnification lens was used with a phosphor beam-monitor and PCO 4000 CCD camera, such that the effective pixel size was 0.19um. Exposures of 20ms were taken at a rate of $2s^{-1}$. A synchronized shutter system was implemented in order to prevent unnecessary exposure between each frame.

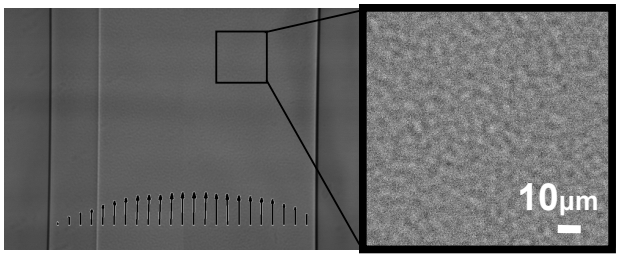

Figure 2. Typical raw X-ray phase contrast image of flowing blood contained with cylindrical vessel. Magnified inset demonstrates the characteristic speckled interference pattern constituting the signal used for PIV. A standard velocimetric profile, showing minimum flow velocities at the wall and maximum in the center, is shown.

Preprocessing of the images before PIV analysis was found to significantly increase the signal to noise ratio. The first step was the average subtraction of the images, taking the average from a distant part of the image sequence in order to prevent bias against very slow moving particles. The average-subtracted images were then Fourier mask filtered to remove the regular streaks caused by the monochromator, taking care not to eliminate those spatial frequencies prominent in the speckle pattern.

We then applied a single-image phase retrieval method to the images. The reconstructed projected thickness is derived in Paganin et al. [1]; additionally, due to the weakness of absorption and significant levels of noise, we make use of a Tikhonov regularization parameter (recently employed to great effect in Groso et al. [11] and Friis et al. [12]). The following equation for the projected thickness $T(\mathbf{r}_\perp,\lambda)$ then applies:

$$T(\mathbf{r}_\perp,\lambda) = -\frac{1}{\mu}\log_e \mathbf{F}^{-1}\left\{ I_0\mu \frac{\mathbf{F}(I(\mathbf{r}_\perp,\lambda))}{\mu + z\delta\mathbf{k}_\perp^{\,2} + \varepsilon}\right\}, \quad (1)$$

where $\mathbf{k}_\perp$ describes the spatial frequencies dual to transverse spatial coordinates $\mathbf{r}_\perp$. ε is the regularization parameter which is inversely proportional to the signal-to-noise ratio. For a two-component sample, such as represented by red blood cells inside the plasma matrix, μ and δ are given by the difference between refractive indices of the two materials [13]. The denominator describes a low-pass band filter. ε was determined by inspection of both the images themselves (the filter's amplification of low-frequency noise is well documented [14]) and the cross-correlation peaks of consecutive images.

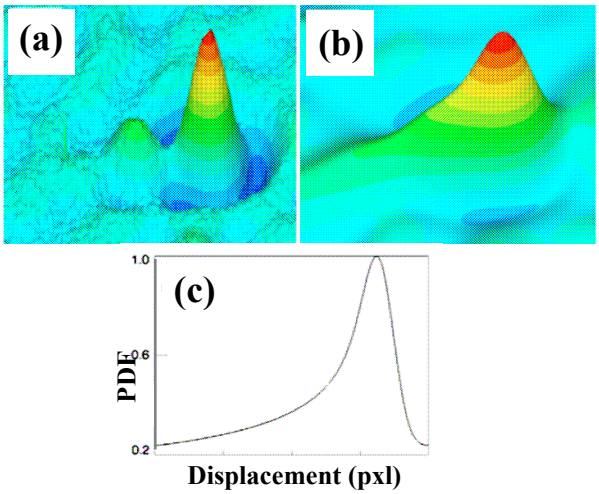

Figure 3. Cross-correlation peak a) before and b) after the application of phase retrieval. The relevant region of the full interrogation window has been magnified for clarity. In (c), the theoretical PDF for parabolic flow of finite sized particles is shown for comparison.

For the latter, each image was segmented into multiple interrogation windows 256 x 256 pixels in area. The difference between conventional PIV and X-ray phase contrast PIV is seen in the form of the cross-correlation peaks. The term *particle* imaging is slightly misleading here as we are in fact only indirectly measuring the particle (red blood cell) displacement from the consequent variation in the interference pattern. At high spatial resolution, the cross-correlation peaks of the speckle images reveal what the eye cannot see, that is at least one strong ring around the central peak, of intensity *below* the noise skirt. Figure 3 shows the cross-correlation peaks for an interrogation region at the capillary centre, both before (a) and after (b) phase retrieval. Application of phase retrieval with a suitably chosen regularization parameter significantly reduces the noise in the correlation and, once the ring has just disappeared, yields substantially better definition of the peak profile.

Standard PIV may then be applied after the phase retrieval to optimally measure the most likely particle displacement for each interrogation region. The resulting velocity profile across

the vessel diameter represents only the modal velocity and as such is not a three-dimensional measurement since it does not take into account the out-of-image-plane variation in flow. For a more complete measurement, we use the fact that each cross-correlation peak represents a probability density function (PDF) of the velocity within the measurement volume [2]. This is clearly demonstrated in figure 3c, which shows the theoretical peak formed by the convolution of a PDF with a Gaussian function whose FWHM corresponds to twice the finite particle width. From the PDF we may derive the expected value, or average velocity within the volume. Integration yields the projected velocity. If we assume axial flow symmetry, consistent with a cylindrical geometry, a simple tomographic reconstruction of the radial profile (based on the inverse Abel-transform) is possible. We used a 6^{th} order even polynomial to fit to the projected velocity. Note that we do not regard the time-smearing of the peaks as significant: the exposure-time-to-Δt ratio of 20ms to 500ms is small and as such, the increased accuracy to be gained through a Richardson-type extrapolation may be assumed negligible [2].

Figure 4 shows the projected velocity (i.e., the line integral of velocities along the direction of propagation) which is directly calculated from the cross-correlation peaks after phase retrieval. At ε values close to the optimal, the result is somewhat insensitive to ε; we have used $\varepsilon = 800\mu$. Figure 4b shows the final reconstructed radial velocity profile. The shape and magnitude of the profile is consistent with the expected Poiseuille circular pipe flow. We note that while the velocity is greater than zero at the radius corresponding to the capillary wall, this is thought to be a direct result of the finite interrogation window size.

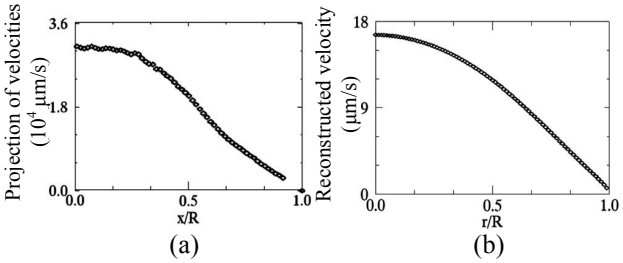

Figure 4. a) Sum of velocities through projection (calculated directly from cross-correlation peak integral) and b) reconstructed radial velocity profile. (a) and (b) represent the forward and inverse Abel transforms respectively.

CONCLUSIONS

We have demonstrated the utility of phase retrieval as a method for the improvement of high-resolution phase contrast images for PIV flow measurement. Additionally, we have obtained a 3-dimensional velocity measurement from a single-image X-ray phase contrast sequence in reconstructing the radial flow profile of blood flowing through a cylindrical capillary tube.

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REFERENCES

[1] Paganin D., Mayo S.C., Gureyev T.E., Miller P.R., and Wilkins S.W. (2002), Simultaneous phase and amplitude extraction from a single defocused image of a homogeneous object. *Journal of Microscopy*, 206(1):33–40

[2] Fouras A., Dusting J., Lewis R., and Hourigan K. (2007), Three-dimensional synchrotron x-ray particle image velocimetry. *Journal of Applied Physics*, 102(6).

[3] S. Berger A. and Jou L. D. (2000), Flows in Stenotic Vessels, *Annual Review of Fluid Mechanics*, **32**: 347.

[4] Bonn D., Rodts S., Groenink M., Rafai S., Shahidzadeh-Bonn N., and Coussot P. (2008), Some applications of magnetic resonance imaging in fluid mechanics: Complex flows and complex fluids. *Annual Review of Fluid Mechanics*, 40:209–233

[5] Lee S.J. and Kim G.B. (2003), X-ray particle image velocimetry for measuring quantitative flow information inside opaque objects. *Journal of Applied Physics*, 94:3620–3623

[6] Kim G. B. and Lee S. J. (2006), X-ray PIV measurements of blood flows without tracer particles, *Experiments in Fluids*, 41:195

[7] Wilkins S.W., Gureyev T.E., Gao D., Pogany A., and Stevenson A.W. (1996), Phase-contrast imaging using polychromatic hard x-rays. *Nature*, 384:335–338.

[8] Im K.S., Fezzaa K., Wang Y.J., Lui X., and Lai MC. (2007), Particle tracking velocimetry using fast x-ray phase-contrast imaging. *Applied Physics Letters*, 90(9).

[9] Kitchen M. J., Paganin D., Lewis R. A., Yagi N., Uesugi K., and Mudie S. T. (2004), On the origin of speckle in x-ray phase contrast images of lung tissue, *Physics in Medicine and Biology*, 49:4335.

[10] Momose A. (2005), Recent advances in X-ray phase imaging. Japanese Journal of Applied Physics 44: 6355-6367.

[11] Groso A., Abela R., and Stampanoni M. (2006), Implementation of a fast method for high resolution phase contrast tomography, Optics Express 14: 8103-8110.

[12] Friis E. M., Crane P. R., Pedersen K. R., Bengtson S., Donoghue P. C. J., Grimm G. W., and Stampanoni M.,

(2207), Phase-contrast X-ray microtomography links Cretaceous seeds with Gnetales and Bennettitales, *Nature* 450: 549-552**.**

[13] Gureyev T. E., Stevenson A. W., Paganin D. M., Weitkamp T., Snigirev A., Snigireva I., and Wilkins S. W., (2002), Quantitative analysis of two-component samples using in-line hard X-ray images, *Journal of Synchrotron Radiation* 9 (Part 3), 148-153.

[14] Paganin D., Barty A., McMahon P. J., and Nugent K. A. (2004), Phase retrieval using coherent imaging systems with linear transfer functions, *Journal of Microscopy* 214 (1), 51-61.