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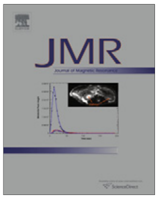

Time resolved velocity measurements of unsteady systems using spiral imaging

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ABSTRACT

Spiral imaging has been assessed as a tool for the measurement of spatially and temporally resolved velocity information for unsteady flow systems. Using experiments and simulated acquisitions, we have quantified the flow artefacts associated with spiral imaging. In particular, we found that despite the adverse effect of in-plane flow on the point spread function, for many physical systems the extent of blurring associated with spiral imaging is marginal because flows represented by high spatial Fourier coefficients, which would be those most affected by the distortion of the point spread function, exist at the physical boundaries of the flow and are therefore associated with much smaller velocities than are characteristic of the bulk flow. The necessity for a flow imaging technique which is robust to the accrual of velocity proportionate phase during imaging was demonstrated in an experimental comparison of spiral imaging and echo-planar imaging (EPI) applied to turbulent flow in a pipe. While the measurements acquired using EPI accrued substantial velocity proportionate phase, those acquired using spiral imaging were not significantly affected. High temporal velocity measurements using spiral imaging were demonstrated on turbulent flow in a pipe (image acquisition time 5.4 ms; 91 frames per second), which enabled the transient behaviour of wall instabilities to be captured. Additionally, the technique was applied to a multiphase flow system, where the wakes behind single rising bubbles were characterised. Spiral imaging thus seems an auspicious basis for the measurement of velocity fields for unsteady flow systems.

1. Introduction

Any flowing system which includes some source of instability will demonstrate transient deviations from the time-averaged flow field. These unsteady flow characteristics occur for systems as diverse as turbulent flow in a pipe and multiphase flow. To better understand such transient features it is highly desirable to obtain quantitative, temporally and spatially resolved velocity information. Magnetic Resonance Imaging (MRI) holds several unique advantages over other techniques for the measurement of this type of information, such as particle imaging velocimetry [1] or laser Doppler anemometry [2], including being completely non-invasive (tracers or particles are not required) and being non-optically based (which permits measurements in opaque systems and at any orientation). The principal disadvantage of MRI is that the measurements are slow to acquire relative to the time-scales of the transient flow features under observation. Only the fastest MRI techniques are capable of producing 'snap-shots' of these ephemeral fluid phenomena. In general, this limits acquisitions to single-shot, echo-planar type sequences [3,4]. Even if sufficient time resolution can be achieved, imaging these systems holds additional challenges. In addition to the position dependent ('zeroth moment') phase used for image encoding, some velocity dependent ('first moment') phase may be accrued during imaging, as distinct from velocity proportionate phase which may be purposely applied prior to imaging for velocity encoding. The principal problem for velocity imaging of unsteady systems is that first moment imaging phase cannot be removed by subtraction of an image acquired using an increment in velocity encoding gradient (the conventional approach) because these two images will have been exposed to different velocity fields. For application to fast flows, this can introduce significant image artefacts, and undermines the quantitative nature of phase-contrast velocimetry.

Blipped echo-planar imaging (EPI) [3] is the most commonly used MRI protocol that possesses the temporal resolution sufficient to characterise highly transient flow features. Most commonly, EPI acquires the entire $\boldsymbol{k}$-space raster in a rectilinear fashion following a single excitation, while using a spin-echo to ensure that off-resonance effects are refocused when the centre of $\boldsymbol{k}$-space is acquired. EPI, however, traverses the phase direction in a unidirectional manner, which leads to significant first moment weighting by the time the centre of $\boldsymbol{k}$-space is reached. Tayler et al. [5] proposed an EPI based sequence which somewhat overcame this problem by acquiring both velocity encoded and phase reference data from a single excitation (which were therefore exposed to similar velocities). However this technique does not explicitly compensate for the accrual of first moment imaging

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phase, and may still be susceptible to flow artefacts. Additionally, it is highly dependent upon favourable relaxation times, and the need to acquire multiple sequential images increases the acquisition time beyond that potentially useful for observation of rapidly changing flow fields. The flow compensation of each individual increment in phase gradient has also been demonstrated [6], however this alteration leads to a significant increase in acquisition time, which undermines the usefulness of the technique for application to highly unsteady systems. Thus, it seems sensible to explore the use of alternative $\boldsymbol{k}$-space sampling schemes that minimise the accrual of first moment imaging phase. A single-shot technique which traverses $\boldsymbol{k}$-space in a spiral trajectory [4], which we shall herein refer to as spiral imaging, may hold several advantages in this respect. In particular, the high-power centre of $\boldsymbol{k}$-space is sampled at the start of the sequence when the transverse plane magnetisation is entirely in phase. Additionally, spiral imaging samples all four quadrants of $\boldsymbol{k}$-space in an interleaved fashion, which acts to compensate for the accumulation of first moment imaging phase [7].

Spiral imaging has not yet been employed for velocity measurements outside of the medical community. Velocity encoded, single-shot spiral imaging was first implemented by Gatehouse et al. [8], almost simultaneously with Pike et al. [9] who investigated multi-shot interleaved spiral velocimetry. Both sets of researchers verified the measured average flow rate to be quantitative, prior to applying their respective techniques to the *in vivo* measurement of arterial blood flow. Subsequent to these early works, phase contrast spiral imaging has been employed in several medical studies, primarily centred upon applications in cardiology [10–16]. Previous analyses of spiral imaging have noted that the early sampling of the centre of $\boldsymbol{k}$-space, and the periodic return of all moments of the imaging gradients to zero, rendered the technique highly robust to flow artefacts [7]. Subsequently, however, Butts and Riederer [17] and Gatehouse and Firmin [18] noted that fast (>50 cm s^{-1}) in-plane flows have an adverse effect upon the point spread function (PSF). The PSF is seen to shift in the direction of flow, split into multiple peaks and broaden over several pixels. This behaviour is congruent with the experiments and simulations of Gatehouse et al. [8], who noted that their images fringe and blur respectively in the direction of flow where their flow phantom entered and left the imaging plane, which they identified as being due to the motion of spin isochromats between the start of the sequence, when all low spatial frequencies are sampled, and at its end, when high-resolution information is obtained. Nishimura et al. [19] also simulated acquisitions of spiral imaging in the presence of flow, however they reported that spiral imaging demonstrates minimal flow artefacts even for in-plane velocities in excess of 2 m s^{-1}. This disparity with other studies appears to be due to their simulation of a unidirectional flow phantom of infinite length.

In the present contribution we seek to explore the applicability of spiral imaging towards the quantification of velocity fields for unsteady flow systems. The impact of in-plane flow on the phase image has not been explored to date, and is investigated in the present study using both simulated acquisitions and experiments. With the flow artefacts associated with spiral imaging thereby quantified, we demonstrate the use of spiral imaging for the measurement of velocity fields on some example unsteady flow systems.

2. Simulations

For application to unsteady flow systems, it is important that the accrual of first moment phase during imaging is minimal. It is difficult to demonstrate theoretically that this is the case for spiral imaging because the spiral trajectories used in practice are complex functions of the maximum gradient amplitude and slew rate available [20]. In this section we quantify the extent of flow artefacts for a two dimensional image acquired using a realistic spiral trajectory by simulating the acquisition of spiral images with additional phase accrual originating from the first moment of the imaging gradients. This is possible as the phase accrued while traversing a given gradient waveform is given by:

$$\phi(r,t) = \gamma r \int_0^t g(t)dt + \gamma v \int_0^t tg(t)dt + O(t^3) \tag{1}$$

where γ is the gyromagnetic ratio, r is position in real space and v is the velocity component in the direction of the applied magnetic field gradient. The first term in Eq. (1) represents the zeroth moment phase, which is used for spatial encoding. The second term is the first moment phase, which, if accrued during imaging, gives rise to phase artefacts due to flow. Phase due to higher order terms (e.g. acceleration) may also be accrued, however this is generally small in proportion to the first moment phase. For example, Sederman et al. [21] noted that for single phase flows at a Reynolds number of 5000 (a liquid velocity of 15.1 cm s^{-1} in their system), the maximum fluid acceleration associated with vortex formation was on the order of 40 cm s^{-2}. For an image acquired over 10 ms, the phase accrued due to acceleration is therefore 2.6% of that accrued due to velocity. In the present analysis, phase accrual due to higher moments is considered negligible. The gradient waveform used for all simulations and experiments in this paper was produced by the algorithm of Glover [22] and is shown in Fig. 1. All simulations assumed a spectral width of 357 kHz for a 64 pixel × 64 pixel image with a 5 cm × 5 cm field of view yielding a resolution of 0.78 mm × 0.78 mm. For a given image geometry and velocity field, Eq. (1) was used to generate a first moment phase map for every sampling increment. A set of $\boldsymbol{k}$-space signals was then generated by application of an inverse non-uniform fast Fourier transform

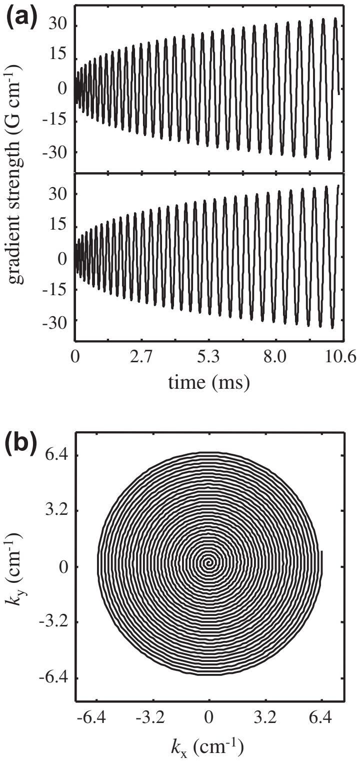

Fig. 1. (a) Spiral gradient waveforms and (b) corresponding $\boldsymbol{k}$-space trajectory used for simulations and experiments.