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Entwicklung einer neuen Methode zur Messung schneller Strömungen mittels Magnetresonanztomographie

A new Magnetic Resonance Imaging method for measurements in high-speed flow

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SYNC SPI, MRV, Venturi, flow measurement, Compressed Sensing

Abstract

Magnetic Resonance Velocimetry (MRV) is a promising method to measure flow velocities inside opaque structures. However, conventional MRV is notably prone to motion induced displacement errors. These errors occur due to the non-instantaneous encoding of spatial coordinates and velocity components. This study aims to identify and to overcome these errors by using a single-point imaging method with synchronized encoding (SYNC SPI). Moreover, the application of compressed sensing is examined to reduce the relatively long acquisition time of this imaging method. A converging-diverging nozzle (venturi) with flow velocities up to the point of cavitation was selected as a test case. Under these conditions, conventional MRV produced significant displacement errors, whereas no such errors appeared in the data of SYNC SPI. Similar data quality was achieved using compressed sensing with a sampling factor of 30%. These experiments prove that SYNC SPI in combination with compressed sensing is a powerful measurement technique to acquire accurate flow velocities in high-speed flows.

Introduction

Magnetic Resonance Imaging (MRI) is commonly used as a medical imaging method to distinguish between different tissue. Moreover, phase contrast (PC) MRI enables two- and three-dimensional insights into the flow velocities in opaque structures. These methods are often referred to as Magnetic Resonance Velocimetry (MRV). In the past decade, MRV has gained increasing interest in the field of fluid mechanics. Preliminary studies showed that MRV is capable of measuring flow velocities in various engineering applications (Benson et al. 2012, Bruschewski et al. 2016, Elkins et al. 2009, Grundmann et al. 2012).
Initially developed for medicine, conventional MRV methods are optimized for imaging speed, not for imaging accuracy. The encoding of spatial coordinates and velocity components is typically not instantaneous. In measurements of moving fluid, the timing differences in the encoding process lead to a distorted geometry and physical wrong flow structures. This type of error

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is commonly referred to as displacement error or spatial misregistration. While this error is often neglected in medical examinations, displacement errors are not acceptable for fluid mechanics studies that require a higher standard of measurement accuracy compared to medicine.

Two different mechanisms generate displacement errors: First, the timing delay in the sequence leads to distortions in the image. This effect can be avoided if all coordinates and velocity components are encoded with the same timing. Secondly, the duration of the individual encoding processes causes blurring of location and velocity. This effect cannot vanish entirely but can be reduced with shorter encoding time.

Depending on the sampling method, these effects are more or less pronounced. In conventional MRV, multiple data points are sampled during a single repetition, which significantly reduces the acquisition time. As a result, the encoding durations and the timing delays are both relatively long, which promotes displacement errors.

In purely phase-encoded techniques such as Single Point Imaging (SPI), the encoding duration and the encoding delays can be designed much shorter. On the downside, only a single data point is sampled each repetition, which significantly increases the acquisition time compared to conventional MRV methods.

Based on this concept, Bruschewski et al. (2018) proposed an SPI method with synchronized encoding (SYNC SPI) to overcome displacement errors. It was demonstrated that SYNC SPI produced reliable results in flows which could not be measured with any conventional MRV method. However, the acquisition time was significantly longer than with conventional MRV.

A promising method to decrease the acquisition time without a significant loss in data quality is compressed sensing. Candés et al. (2004) and Donoho et al. (2006) first proved that a randomly undersampled data set could have a similar data quality than the fully-sampled data set if reconstructed iteratively. Thereupon, Lustig et al. (2005) demonstrated the application of compressed sensing in MRI to accelerate the acquisition. Since then, a few studies investigated the use of undersampled MRI in clinical (Block et al. 2007) and engineering applications (Holland et al. (2014)). In these studies, compressed sensing showed reliable results. The applicability of compressed sensing for SYNC SPI is examined in this study.

Methods

This study compares SYNC MRI with a conventional MRV method similar to the 4Dflow sequence proposed in Markl et al. (2012). For both methods, the sequence design, the effect of their encoding on a moving fluid particle, and the sampling pattern are displayed in Fig. 1. The conventional method uses frequency encoding to reduce the measurement time. On the downside, the encoding process is not instantaneous, and the encoding time is comparatively long, which promotes displacement and other flow related errors.

Much shorter encoding times are achieved using SYNC SPI. In this method, no encoding takes place during readout. As a result, the encoding process is significantly shorter, and it can be designed such that the encoding of spatial coordinates and velocity components is synchronized. Therefore, both mechanisms that generate displacement errors are avoided as much as possible. The detailed design of the encoding process is explained in Bruschewski et al. (2018).

On the downside, the measurement time of SYNC SPI is significantly longer than with conventional MRV. As a remedy, compressed sensing is applied here to shorten the measurement time to some extent. The data is randomly undersampled. Data points that are not sampled are set to zero. This data is referred to as zero filled. An iterative reconstruction similar to Lustig et al. (2005) is used to recover the physical data from the undersampled data sets. The reconstruction is realized by minimizing the sparse representation of the data in a known transform domain. In this study, the sparse transformation is determined as the Total Variation (TV). Similar to the approach proposed in Lustig et al. (2005), the optimization is solved in its unconstrained Lagrangian form using projected conjugated gradients. Suggestions from Holland et al. (2014) are implemented to optimize the reconstruction for quantitative velocity data.

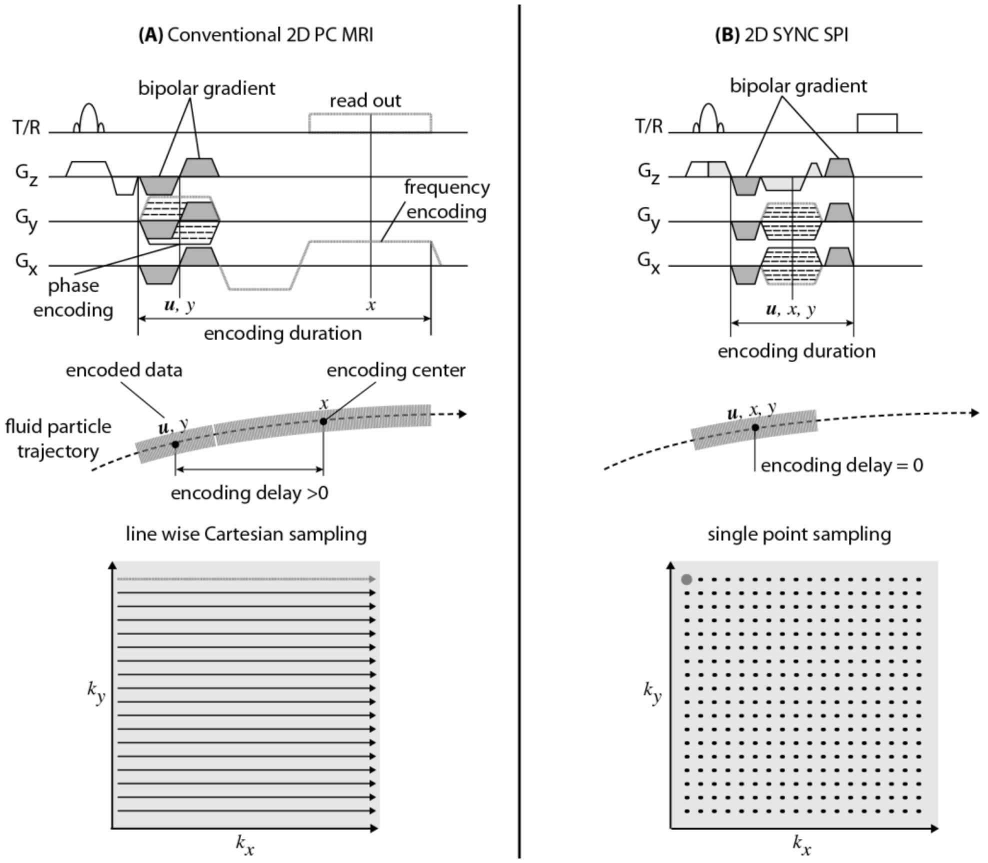

Figure 1: Sequence diagrams of conventional MRV (A) and SYNC SPI (B). The effect of the encoding on a moving fluid and the resulting sampling pattern are shown below the diagrams.

Experimental Set Up

An axis symmetric converging-diverging nozzle (venturi) with flow velocities up to the point of cavitation was used to investigate the potential of undersampled SYNC SPI. Due to the concentric contraction, the flow strongly accelerates in the axial direction. The venturi and the pipes inside the examination room were made from PMMA as this material matches the magnetic susceptibility of water (Wapler et al. 2014). The design of the venturi and the set up for the MRI measurements are displayed in Fig. 2.

Measurements were performed on a 3 Tesla whole-body Magnetom TRIO (Siemens, Erlangen, Germany) with a resolution of 0.75 mm. This system has a maximum gradient amplitude of 38 mT/m and a maximum slew rate of 170 T/m/s. The scanner is part of the MRI laboratory at the Institute of Fluid Mechanics at the University of Rostock. Unlike most MRI scanner usually used for medical treatments, this laboratory is specifically designed for fluid mechanics application.

The venturi was connected to a flow circuit with a variable speed pump and a 1000 liter tank. The flow medium was purified water with copper sulfate added as a contrast agent. The maximum investigated flow rate was 2.85 l/s, which led to flow velocities of 12 m/s inside the throat of the venturi.

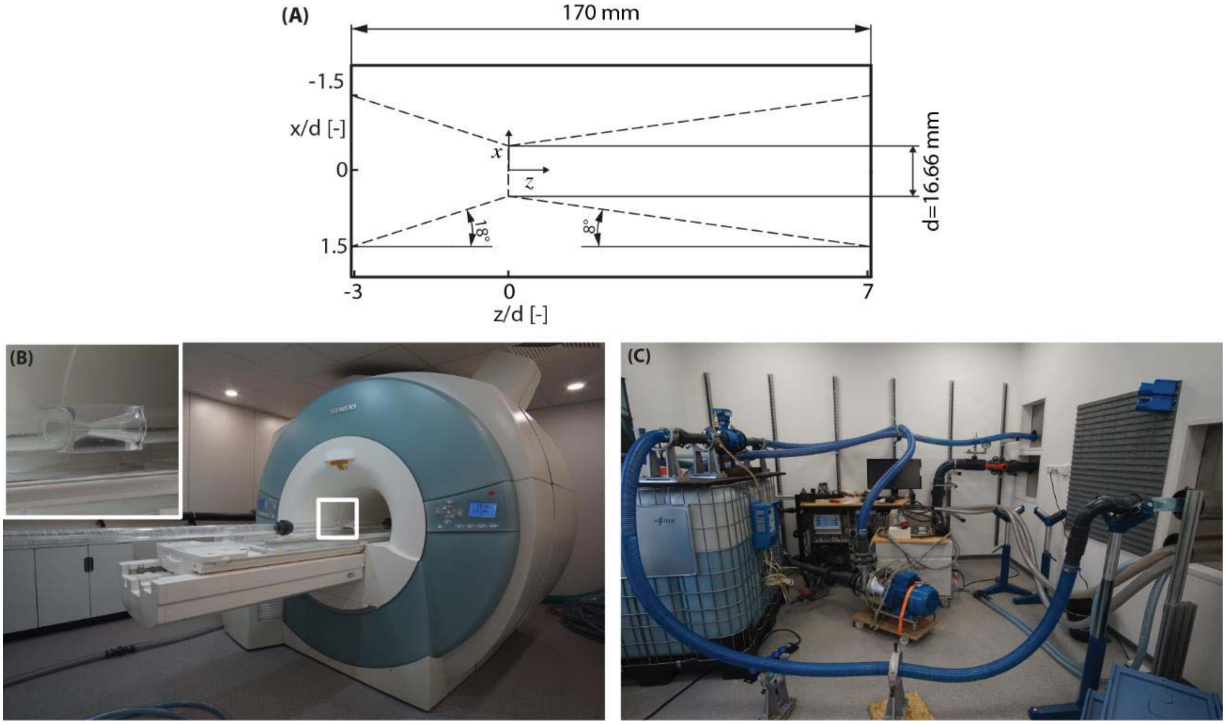

Figure 2: Design of the Venturi (A), set up inside the examination room (B) and the flow supply system (C).

Results

Figure 2 shows the results of the conventional MRV method and the SYNC SPI method at different flow rates. In the image magnitude obtained from conventional MRV (Fig. 3 A), displacement errors appear as distortions in the geometry of the venturi. As described before, this error is related to the encoding delay in the sequence. Also, a significant loss in the image magnitude arises at a flow rate of 2.85 l/s, which is presumably because of flow turbulence.

The velocity fields were segmented with the help of the image magnitude to remove background noise. The results are shown in Fig. 3 B. It can be seen that the velocity field obtained with conventional MRV is shifted downstream. The maximum velocity still occurs near the throat of the venturi, which is however at a wrong position because of displacement errors. In contrast, the images obtained with SYNC SPI show fewer errors. The geometry and flow field are accurately displayed.

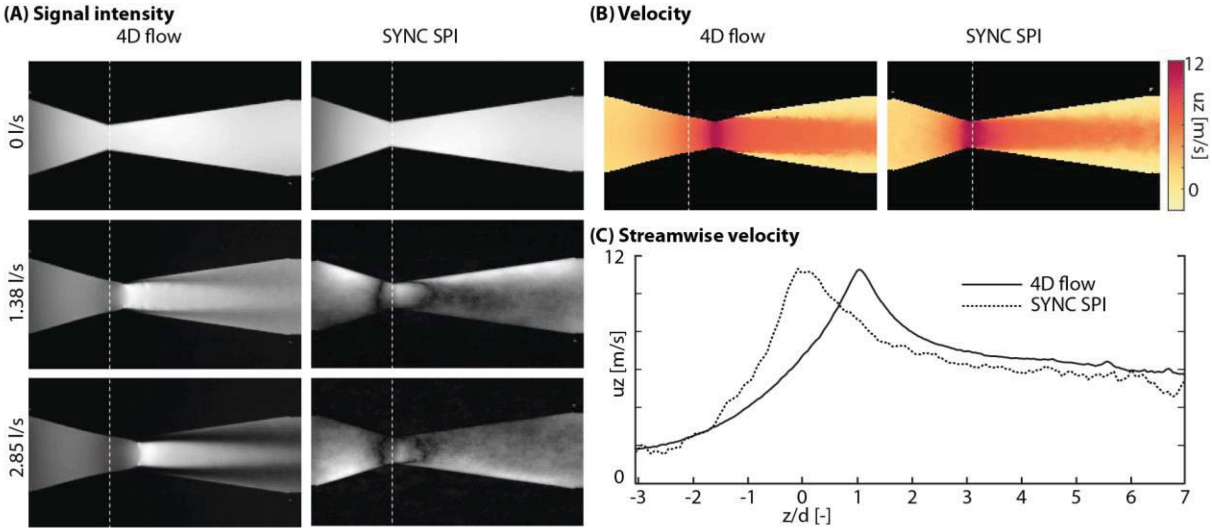

Figure 3: Qualitative and quantitative comparison of conventional MRV and SYNC SPI

Next, the results from the undersampled SYNC SPI data are presented. In the zero-filled magnitude images in Fig. 4 A, noise-like errors are visible across the entire image. These errors vanish almost entirely in the iteratively reconstructed images.

Similar observations can be made in the reconstructed velocity data shown in fig. 4-B. For the zero-filled data, the images appear noisy, especially for low sampling factors. In contrast, no significant deviations are visible in the velocity data after iterative reconstruction.

A quantitative comparison of the undersampled and iteratively reconstructed data and the fully-sampled data is shown in Fig. 5. It can be seen that after the iterative reconstruction, the data is mostly accurate, even for low sampling rates.

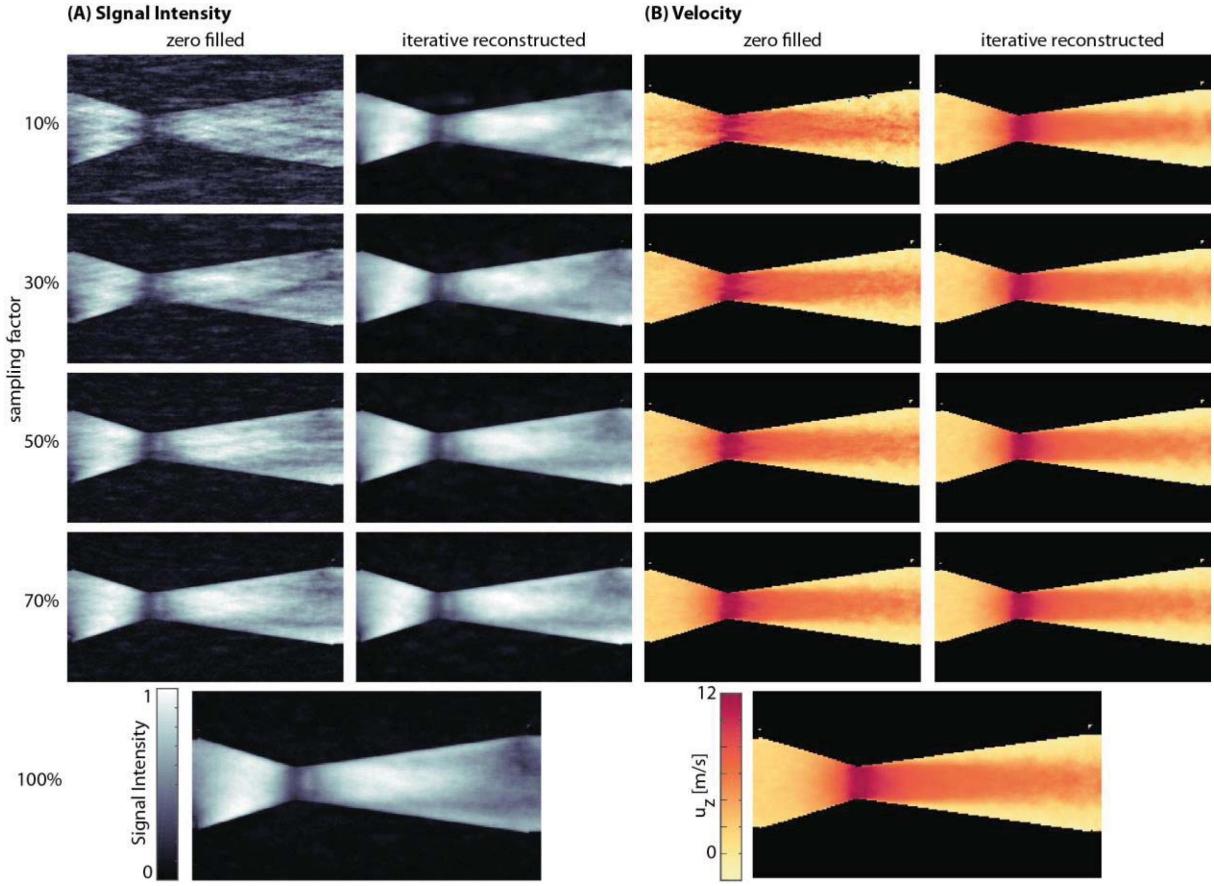

Figure 4: Qualitative comparison of results from undersampled SYNC SPI

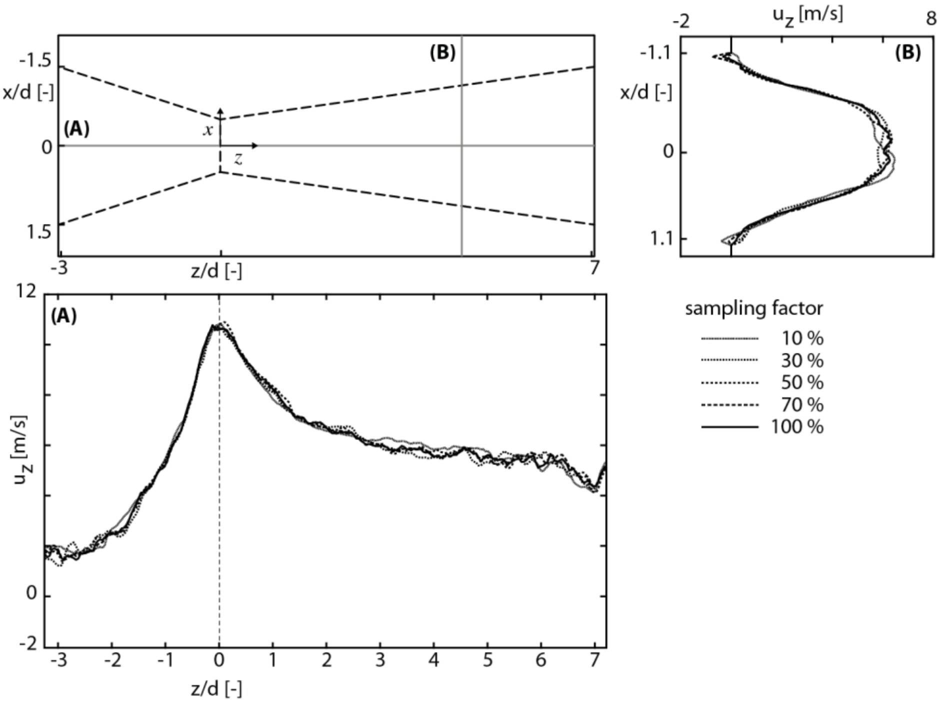

Figure 5: Quantitative comparison of velocity from undersampled SYNC SPI

Discussion & Conclusion

No displacement errors were visible in the experiments using SYNC SPI which reveals that even at flow rates as high as 12 m/s, displacement errors and other flow related errors occur at scales smaller than the voxel size. Furthermore, the experiments confirmed that SYNC SPI is less prone to signal loss due to turbulence. As described before, turbulence leads to accelerated degradation of the MRI signal. This effect is prevented with a short sequence timing as accomplished in SYNC SPI.

In contrast, data obtained from conventional MRV showed significant displacement errors. These results illustrate that clinically used MRV methods are not always suitable for flow experiments which require high accuracy.

The acquisition time has been so far the most significant disadvantage of SYNC SPI. In this study, compressed sensing was used to accelerate the acquisition. The images reconstructed from randomly undersampled data proved that this technique is a promising method to accelerate SYNC SPI while maintaining high measurement accuracy.

However, limitations may arise in measurements in more turbulent flows than investigated here. Increasing turbulence will eventually lead to signal attenuation and generally noisier images. Consequently, iterative reconstruction from an undersampled data set might not be possible because the underlying data quality is not sufficient anymore.

In conclusion, SYNC SPI is a promising method to produce 3D velocity data with high accuracy. In combination with compressed sensing, the measurement time is reduced, which makes the acquisition considerable more efficient.

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