5th International Conference on Experimental Fluid Mechanics – ICEFM 2018 Munich
Munich, Germany, July 2-4, 2018

MRI Flow Lab: A Dedicated MRI Laboratory for Quantitative Flow Measurements and Method Development

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Abstract

A unique Magnetic Resonance Imaging (MRI) laboratory has been installed at the Institute of Fluid Mechanics at the University of Rostock. The laboratory is specifically designed for experiments in fluid flows. The whole-body MRI system, a 3 Tesla Siemens MAGNETOM Trio, can be integrated into various flow circuits with water and other MRI-compatible fluids. The research focuses on the development and validation of new flow quantification methods for fluid mechanics applications. As a result of the commissioning phase, a new velocity-sensitive MRI sequence is presented which provides a significant improvement in measurement accuracy compared to the commonly used methods. As another result of the commissioning phase, a sequence is presented which allows time-resolved measurements in fluid flows. To the current state, this method enables frame rates up to 40 Hz for non-velocity-sensitive MRI and frame rates up to 16 Hz for velocity-sensitive MRI. The two presented sequences are regarded as an important step to increase the applications of MRI in fluid mechanics. So far MRI has been heavily limited to stationary or periodic flows with relatively low flow velocities. The long-term aim is to make MRI more available to the field of fluid mechanics and its related industries. The presentation at the meeting will discuss the conception, planning, implementation and commissioning of this laboratory as well as future research opportunities.

1 Introduction

Phase-contrast magnetic resonance imaging (PC MRI) is commonly associated with the medical examination of the cardiovascular system in humans. It provides a three-dimensional insight into the flow structure without requiring optical or physical access to the flow field (Fukushima 1999). The acquisitions can be performed in three dimensions with data rates as high as 100,000 data points per second. On the downside, MRI requires a flow medium with non-zero nuclear spin, for example water protons, and places restrictions on the materials used in the MRI examination room. Most metals cannot be used because of magnetic or electro-magnetic interference.

In the past decade, MRI has found increasing application in the field of fluid mechanics (Elkins & Alley 2007, Gladden & Sederman 2013). MRI has been used to acquire various flow properties, such as velocity (Grundmann et al 2012, Bruschewski et al 2016), temperature (Buchenberg et al 2016), Reynolds stresses (Elkins et al 2009) and species concentration (Benson et al 2012) in technical fluid systems. In these laboratory experiments, MRI can produce exceptionally high signal-to-noise ratios, high resolution and sharp contrasts compared to medical (in vivo) imaging. There is tremendous need for new PC MRI methods specifically designed for fluid mechanics application.

Furthermore, all previous studies were conducted on medical MRI systems in clinical facilities. These studies are all characterized by trade-offs regarding the experimental conditions during the measurement. There is no question that clinical facilities are not the optimum environment for high accuracy fluid mechanics experiments.

Because of these reasons, a new MRI flow laboratory has been installed at the Institute of Fluid Mechanics at the University of Rostock. The research primarily focuses on the development and validation of flow quantification methods for fluid mechanics applications. In addition, the unique setup of the laboratory offers various other possibilities for engineering, medicine and science, for example for studies which would not be permitted on medical MRI system because of the strict clinical regulations.

Design of the MRI Flow Lab

The MRI flow laboratory is approved by the DFG (German Research Foundation) under the Major Research Instrumentation Program. The main objective in designing this facility was to provide a highly specialized laboratory for quantitative MRI measurements in fluid flows and for the development of new MRI-based flow quantification methods. Particular attention was paid to the flexibility and upgradability of the laboratory for future research tasks as well as operational safety and well-controlled measurement conditions.

Figure 1 shows a picture of the completed MRI flow lab. The central element of the laboratory is a 3 Tesla whole-body MRI system, a Siemens Magnetom TRIO (Erlangen, Germany), with gradient amplitude 38 mT/M and gradient slew rate 170 T/m/s. The bore of the scanner has a diameter of 600 mm with a spherical measurement volume of 500 mm diameter.

The unique layout of the laboratory allows quick and easy flow installations. The examination room is screened against electromagnetic noise and interference. All piping systems that connect the pumps with the flow models inside the MRI scanner are placed through electromagnetic filters in the walls. A total of six exchangeable filter panels can be used for various flow circuit installations in between rooms.

Figure 1: Picture of the MRI flow lab showing the MRI scanner and a flow circuit installation.

Sequence Development – Improved Measurement Accuracy

In routine flow measurements based on PC MRI techniques, it is often observed that the fluid velocity leads to errors in the measured geometry. This effect is known as misregistration (Bernstein et al 2004). Because the encoding process in common MRI techniques is not instantaneous, the spatial coordinates and the velocity data are encoded at different times. As a result, the reconstructed signal of the fluid flow appears at locations that the fluid particles have never physically occupied. Until now, MRI has been largely limited to flow velocities smaller than 1 m/s mainly because of the measurement errors that arise with high flow velocities.

Most pulse sequences, including modern ultra-short echo time methods, are based on spin-warp imaging. Inevitably, in these pulse sequences, there is a delay between the encoding events which leads to misregistration. Even though such sequences can be used for rapid flow measurements, they still are limited in velocity magnitude because of misregistration.
On the other hand, purely phase-encoded imaging methods, known as single point imaging (SPI), provide more flexibility in designing the timing of encoding events (Bernstein et al 2004). All encoding events can be synchronized in a way that the encoding delay is effectively zero. Based on this concept, a new pulse sequence with synchronized encoding, named SYNC SPI, is designed which allows misregistration-free PC MRI.
This sequence is evaluated with a high-velocity flow with central contraction. For comparison, a conventional gradient echo PC MRI method with Cartesian encoding is evaluated. This method is regarded as the state-of-the art in medical flow quantification (Markl et al 2012).
Figure 2 shows the axial velocity in the middle plane of the central contraction. Two misregistration effects can be identified. The results of the conventional PC MRI method show a pronounced distortion of the channel geometry at the edge of the contraction. The effect is clearly seen in the enlarged image inset. The sharp edge of the contraction appears round in these results. The mechanism of this error is connected to the encoding delay between the frequency-encoded z-coordinate and the phase-encoded y-coordinate. The SYNC SPI sequence does not show these errors. The channel geometry is correctly captured by this sequence.
A second misregistration effect can be identified in the flow field. In the results of the conventional PC MRI method, the axial velocity is increased after the fluid enters the contraction. This is physically wrong. The correct flow behavior is shown in the SYNC SPI data: the flow velocities increases right at the contraction because of the reduction in cross-sectional area. The velocity error in the conventional PC MRI method can be related to the delay between the encoding of the z-velocity and the encoding of the z-coordinate.

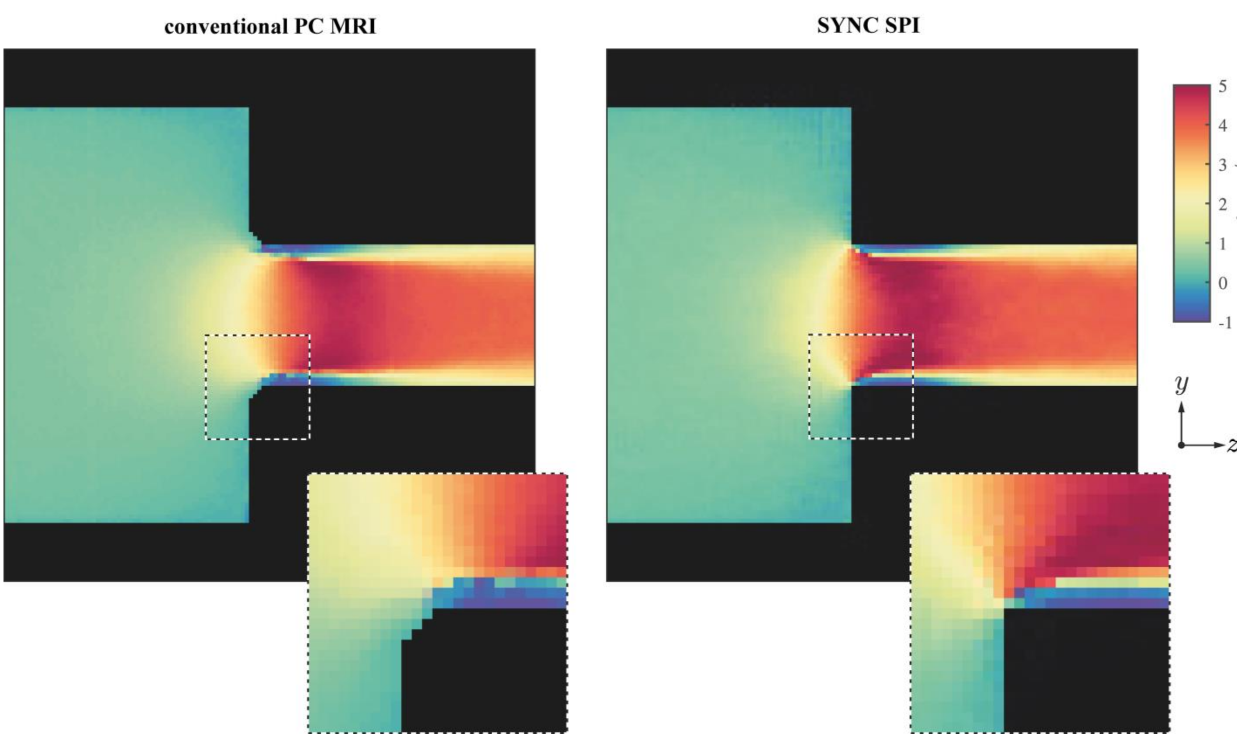

Figure 2: Axial velocity field in the stenosis test case measured with a conventional Cartesian PC MRI sequence and with the SPI sequence with synchronized encoding (SYNC SPI). A two-dimensional slice of the three-dimensional acquisition is shown.

Figure 3 shows the calculated flow rate from the MRI data for all stream-wise positions. The results of the conventional PC MRI method show a strong decrease in flow rate before and after the fluid passes through the contraction. The maximum deviation is -35% of the nominal flow rate. A second deviation is visible in the region downstream of the contraction in which the conventional PC MRI method results show a +6% higher flow rate. It is obvious that the deviation in flow rate coincide with the misregistered flow field shown in Fig. 2.
Unlike to the conventional PC MRI results, it can be seen in Fig. 3 that the SYNC SPI sequence produces mostly consistent flow rate results. Shortly upstream to the contraction, there is a region in which the flow rate oscillates within +/- 6%. The source of this error is not regarded as misregistration. Instead, the deviation is related to Gibbs ringing effects at the sharp edge between water and wall material in z-direction which can be removed by enlarging the image matrix.
In summary, it is shown that the conventional PC MRI method produced severely distorted results. Accordingly, such PC- MRI sequence might not be suitable for flow quantification in flow systems with similarly high flow velocities. The main advantage of the SYNC SPI sequence is the fact that misregistration is effectively removed. There are virtually no limits regarding the measurable flow velocities. On the downside, the point-wise acquisition of the SYNC SPI leads to comparably long measurement times.

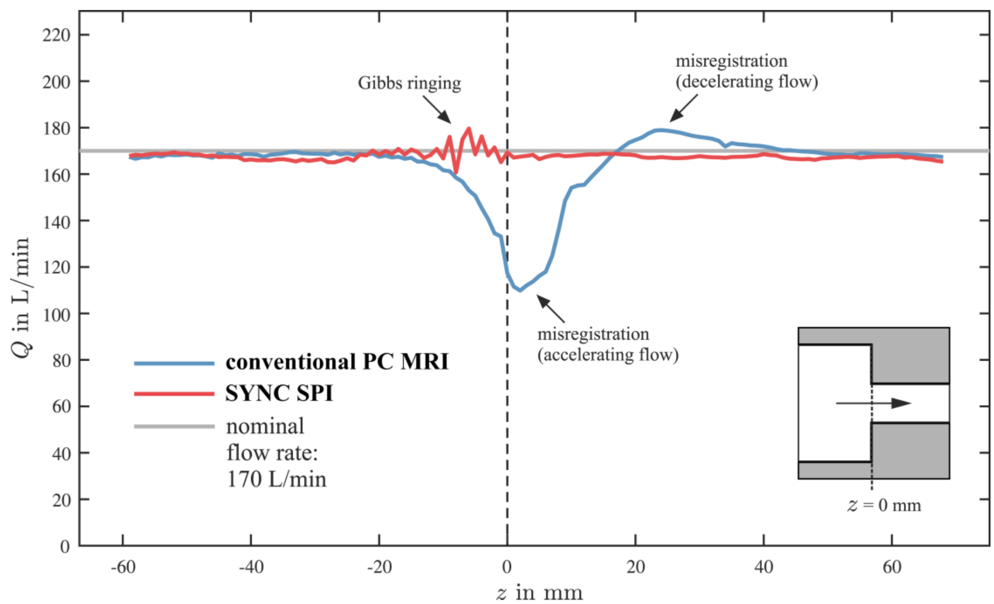

Figure 3: Computed flow rate in the stenosis test case for the velocity data shown in Fig. 2.

Sequence Development – Improved Temporal Resolution

Due to the relatively low temporal resolution, PC MRI is typically limited to stationary laminar or stationary turbulent flows. A fully-sampled PC-MRI image with matrix size 128 x 128 typically results in a temporal resolution not much higher than 1 Hz.
Recent progress in MRI has demonstrated that a much higher temporal resolution is possible without major trade-offs in measurement quality (Holland et al 2010). Short acquisition times are achieved via under-sampling, hence less data is sampled per measurement. Iterative reconstruction algorithm adapted from Lustig et al (2007) is used for image reconstruction to suppress errors related to under-sampling.
The potentials of time-resolved MRI for fluid mechanics research are demonstrated with a transient two-phase flow experiment. Compressed air is added to a water flow in a straight pipe resulting in strongly transient characteristics.

Figure 4 shows the results of a velocity-sensitive sequence with 16 Hz frame rate. All velocity values that belong to a low signal magnitude were removed. The datasets provide two quantitative information: the distribution of water in the pipe and the water velocity in axial direction. It can be seen that the conventional reconstructed images show pronounced reconstruction artifacts. These errors are removed by iterative reconstruction.

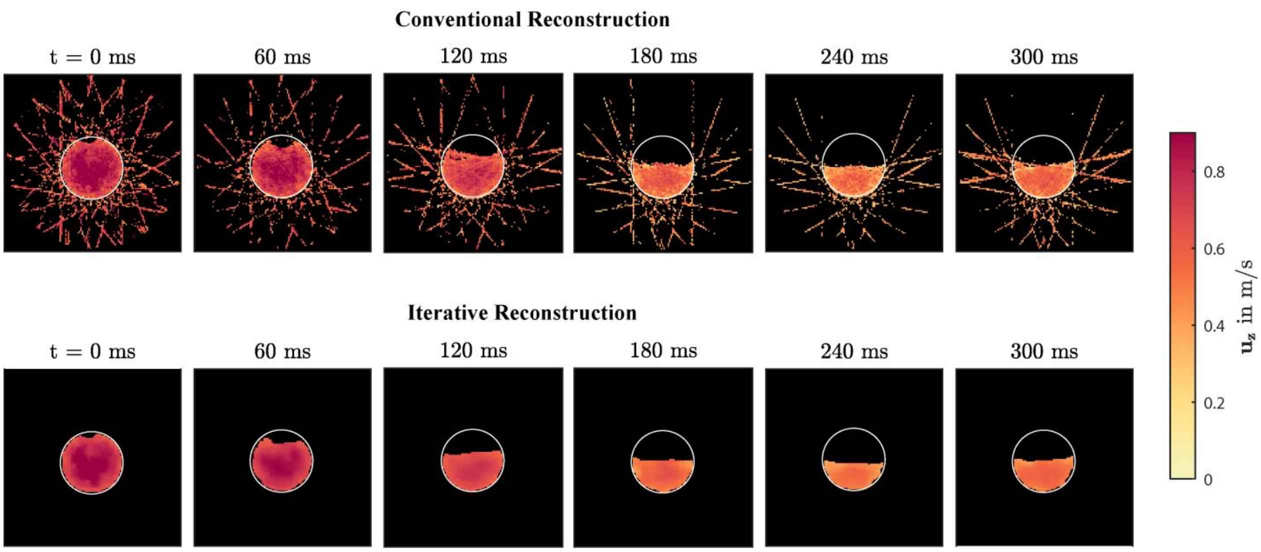

Figure 4: Results of the two-phase flow experiment with velocity-sensitive encoding. The white circles show the pipe contours.

Conclusion

The new MRI laboratory at the University of Rostock provides a completely new field of application for MRI-based flow quantification. The unique integration of a whole-body MRI system in a dedicated flow laboratory provides unprecedented possibilities for fluid mechanics research and flow engineering. As a result of the commissioning phase, two novel PC MRI pulse sequence were developed.

One sequence was designed to improve the accuracy of PC MRI and remove flow-related errors. This sequence is an important step towards more accurate flow quantification with PC MRI. The other presented sequence was designed to achieve high temporal resolution in MRI-based flow measurements. This sequence can be applied to transient single-phase or multi-phase flows in which at least one fluid phase contains water protons or other measurable nuclei.

The two presented sequences are regarded as an important step to increase the applications of MRI in fluid mechanics. So far MRI has been heavily limited to single-phase stationary or periodic flows with relatively low flow velocities. The presentation at the meeting will discuss the conception, planning, implementation and commissioning of this laboratory as well as future research opportunities.

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