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MRI Flow Lab – Magnetresonanzlabor für Strömungsmechanische Untersuchungen

MRI Flow Lab – A dedicated Magnetic Resonance Laboratory for Flow Quantification

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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. A common error in flow MRI is misregistration which is caused by the spatial displacement of the signal in fluid flows. As a result, the signal appears at locations that the fluid particles have never physically occupied. Based on a high-velocity flow test case, it is shown that the newly developed sequence produces results free of misregistration errors. In comparison, conventionally used sequences show flow field deviations of up to 100% in the same experiment. The presented sequence is regarded as an important step to increase the applications of MRI in fluid mechanics. So far MRI has been heavily limited to 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.

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 concentra-

tion (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. Many measurement errors that can be argued as negligible for in vivo imaging become important in these measurements. For this reason, there is tremendous need for new PC MRI methods to achieve better measurement accuracy in these experiments. So far, none of the commonly used methods have been 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.
To improve these conditions, 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.
An example of a future flow circuit installation is depicted in Fig. 2. In this setup, a water circuit capable of a volumetric flow rate of up to 10,000 liters per minutes combined with a 300 mm diameter test section can be used to achieve fully-turbulent flow conditions at a Reynolds number of up to 800,000. This installation will enable wind-tunnel-like measurement with MRI.

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

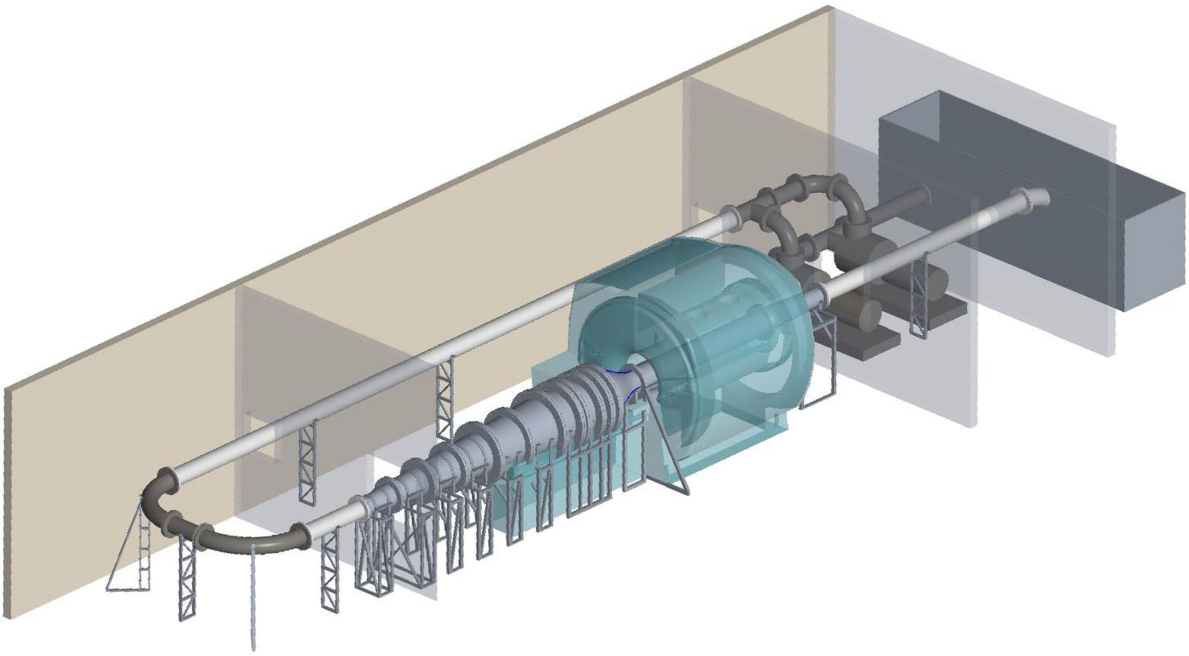

Fig. 2 Possible future flow circuit installation.

Sequence Development – Improved Measurement Accuracy

After successful installation of the laboratory, one of the first tasks was to assess the measurement accuracy of the commonly used PC-MRI methods. Sources of systematic measurements errors were identified, and improved PC MRI sequences were programmed and tested. In the following paragraphs, a new PC MRI sequence is presented which was specifically designed for accurate velocity measurement in high-velocity flows.
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 information 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. The spatial displacement of the signal increases with flow velocity and with the time delay between the encoding events. Until now, PC MRI has been largely limited to flow velocities smaller than 1 m/s mainly because of the misregistration errors that arise with high flow velocities.
Most pulse sequences, including modern ultra-short echo time methods, are based on spin-warp imaging (O'Brien et al 2009, Kadbi et al 2015). In these pulse sequences, at least one spatial coordinate is encoded via frequency encoding. The velocity data and other spatial coordinates must be encoded before the frequency encoding event. Inevitably, there is a delay between these encoding events which leads to misregistration in fluid flows. 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). In previous studies, the applicability of SPI to measure fluid flows has been well-demonstrated (Newling et al 2004). In SPI, there is no frequency-encoding and instead, a single data point of k-space is acquired at a time instance at which no encoding event is taking place. Therefore, all encoding events can be synchronized in a way that the encoding delay is effectively zero. Based on this concept, a new pulse sequence is designed which allows misregistration-free PC MRI.
The developed SPI sequence with synchronized encoding, named SYNC SPI, is evaluated with a high-velocity flow with concentric contraction. The geometry of the test case and the position of the field of view (FOV) are shown in Fig. 3. The three-dimension acquisition has a matrix size of 128 x 128 x 128 pixels and 1 mm^3 resolution. The experimental setup is depicted in Fig. 4. The test case is connected to a pump system capable of 300 Liters per minute and a total capacity of 1000 Liters. The flow rate is monitored using ultrasonic flow meters. The flow medium is purified water with a concentration of 1g/L CuSo4 as contrast agent. The materials of the flow models are PMMA and POM which were selected to match the magnetic susceptibility of water (Wapler et al. 2014).
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). The particular sequence was designed to achieve shortest possible echo time for a given set of gradient moments. However, due to the type of sequence, there are encoding delays, especially between the frequency-encoded position and all other encoding events, which lead to misregistration errors at high flow velocities as applied here.

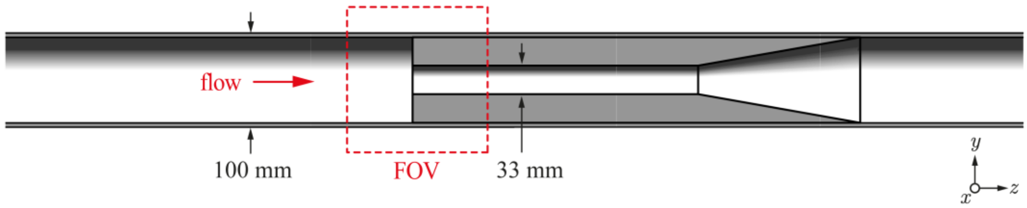

Fig. 3 Setup of the investigated stenosis test case including the field of view (FOV) of the MRI acquisition. A 3 m long pipe for flow development is placed upstream to the contraction.

Fig. 4 Pictures of the experiments with the stenosis test case. A straight pipe, shown on both image parts, connects the pump system with the flow model in the MRI system.

Preliminary Results

Figure 5 shows the axial velocity in the middle plane of the stenosis test case. 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 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. For the conventional PC MRI method, the axial velocity increases 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 is related to the encoding delay between the z-velocity and z-coordinate. Even though the true velocity distribution is not known, the overall accuracy can be measured based on the deviation in the flow rate.

Figure 6 shows the calculated flow rate from the MRI data for all stream-wise positions. The same effects as seen in Fig. 6 can be observed here. 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 coincides with the misregistered flow field shown in Fig. 5. The -35% flow rate error at the contraction is related to the misregistration of the flow velocities in z-direction. The acceleration region that should be located right at the contraction is shifted downstream. The +6% deviation downstream of the contraction can be explained in a similar way. The deceleration region at the end of the flow reversal zone is shifted downstream in the images of the conventional PC MRI method due to misregistration.

Unlike to conventional PC MRI, it can be seen in Fig. 6 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.

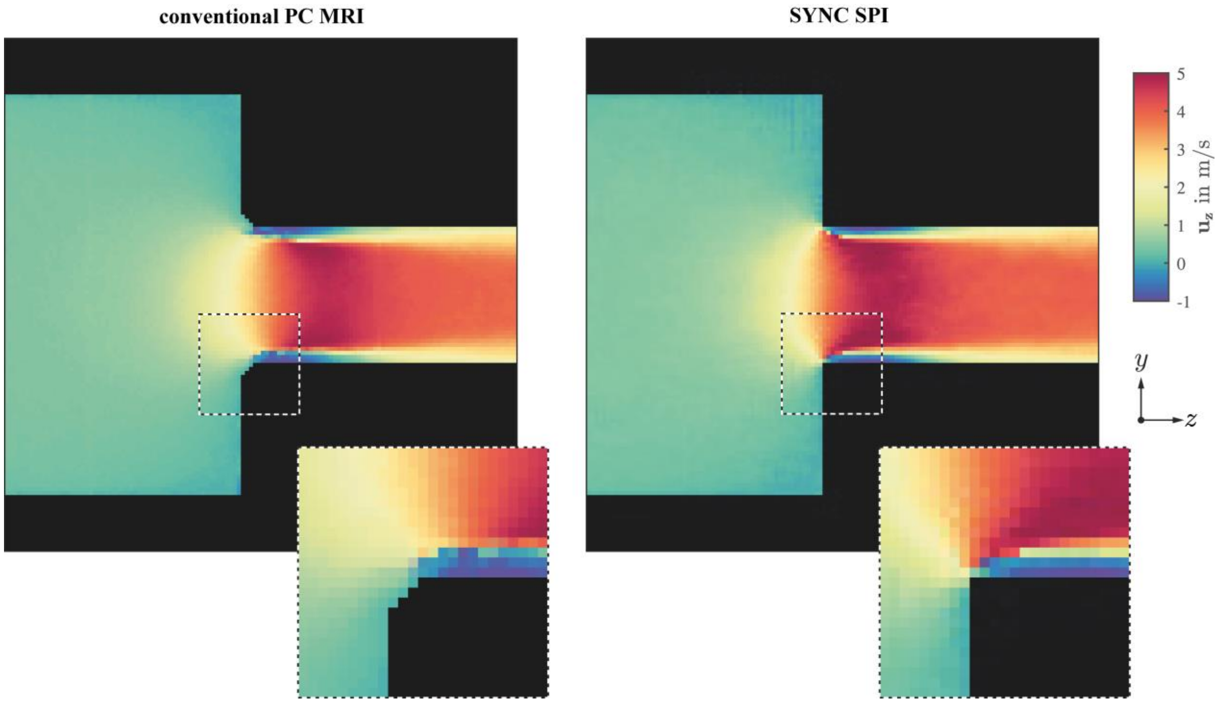

Fig. 5 Axial velocity field in a flow contraction measured with a conventional Cartesian PC MRI sequence and with the SPI sequence with synchronized encoding (SYNC SPI). A two-dimensional slice of the three-dimensional acquisition is shown. The image insets show the misregistration effects at the edge of the contraction.

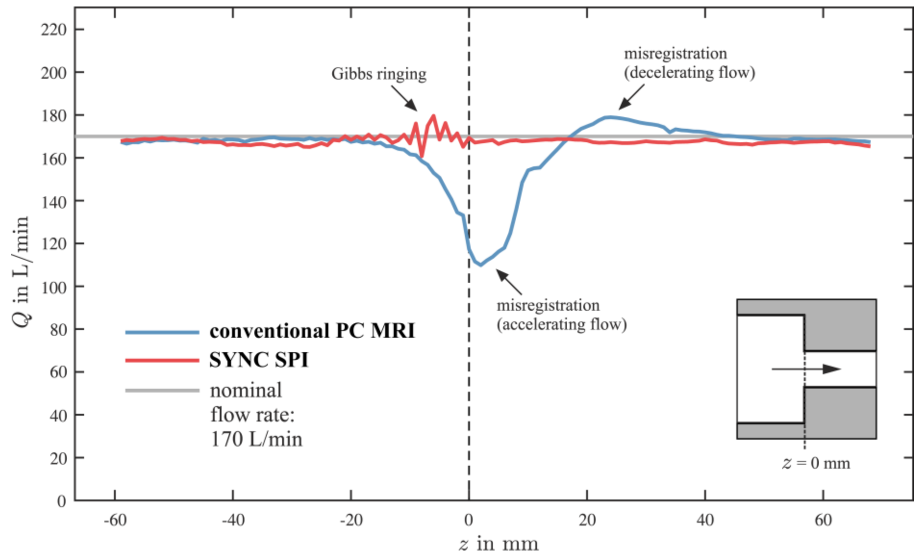

Fig. 6 Computed flow rate in the stenosis test case for the velocity data shown in Fig. 5.

In summary, it was found that the conventional PC MRI method produced severely distorted results in this case. A flow rate deviation of up to 35% was identified as a direct result of misregistration. Accordingly, such PC- MRI sequence might not be suitable for flow quantification in flow systems with similar 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.

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On the downside, the point-wise acquisition of SYNC SPI leads to comparably long measurement time which limits the application of this kind of sequence to non-medical applications. Therefore, this sequences is only suited to measurements in which the emphasis is laid on measurement accuracy rather than imaging speed. This applies to most fluid mechanics experiments.

Conclusion

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, a novel PC MRI pulse sequence was developed.
The sequence was designed to improve the accuracy of PC MRI and remove flow-related errors. Based on a test case with high-velocity flow, it was found that the previously used methods are severely corrupted by misregistration effects that are related to the flow velocity. In contrast, the newly developed sequence allows misregistration-free PC MRI. It was shown that this type of sequence can be applied to fluid flows with velocities much greater than 1 m/s. Future work will be directed towards reducing the acquisition time with under-sampling techniques and iterative image reconstruction.
This sequence is regarded as an important step to increase the applications of MRI in fluid mechanics. So far MRI has been heavily limited to 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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