Fachtagung “Experimentelle Strömungsmechanik”
4. – 6. September 2018, Rostock

Zeitaufgelöste Messungen von Mehrphasenströmungen mittels Magnetresonanztomographie

Towards Time-Resolved Magnetic Resonance Measurements in Multi-Phase Flows

Kristine John, Martin Bruschewski, Sven Grundmann
Institute of Fluid Mechanics, University of Rostock

Magnetresonanztomographie, zeitaufgelöste Strömungsmessung, Mehrphasenströmung
Magnetic Resonance Imaging, time-resolved flow measurements, multi-phase flows

Abstract

This study focuses on the adaptation and further development of time-resolved Magnetic Resonance Imaging (MRI) methods for fluid dynamics applications. For a proof of concept, these measurements were performed in a steady-state flow and in a multi-phase flow of water and air. Time-resolved data acquisition was realized using highly under-sampled radial pulse sequences. Measurements were performed on a 3 Tesla whole-body MRI scanner, a MAGNETOM Trio by Siemens.

To the current state, the implemented method enables frame rates up to 41 Hz for two dimensional measurements of the proton density in a 128 mm x 128 mm field of view with a resolution of 1 mm. Velocity sensitive measurements have been accomplished with frame rates up to 16 Hz. The calculated flow rate of the steady-state pipe flow was slightly underestimated by the under-sampled radial acquisition which will be addressed in future research.

Introduction

MRI is a non-invasive measurement technique commonly known from medical examination which is capable of measuring various flow parameters in three dimensions with relatively short acquisition times and without requiring optical access. Therefore, researches in the field of fluid mechanics have shown increasing interest do adapt these methods for engineering applications (Elkins and Alley 2007). Among others, time-resolved measurements of multi-phase flows are one possible field of application. A prominent example of multi-phase flows is the flow of water and gas through a horizontal channel. These flows occur, for example, in power plants. As only the water phase leads to high signal intensities, this type of flow can be easily visualized using proton-density-weighted MRI measurements. However, standard MRI techniques do not have the required temporal resolution to capture the transient effects in these flows.

To the current state, time-resolved MRI flow measurements have been mainly performed in periodic flows, for example to capture the flow inside the human heart (Markl et al. 2012) or in a model of internal combustion engines (Freudenhammer et al. 2014). In these studies, time resolution was realised by sampling only a fraction of the full data set per measurement. Therefore, the measurement must be repeated several times to capture the required amount of data for every time step of the cycle.

Due to non-periodic characteristics, multi-phase water-air flow cannot be measured with this technique. However, Untenberger et al. (2016) proposed a method to realize time-resolved measurements in non-periodic medical applications. This method is based on a non-linear under-sampling of the data and an iterative reconstruction, which allows very short acquisition times. This method is implemented to realize time-resolved MRI flow measurements in fluid dynamic applications.

MRI Principals

MRI is based on the behaviour of the quantum mechanical spin of an atomic nucleus in an external magnetic field. This imaging method works with any nucleus with a non-zero spin, however, the hydrogen nucleus is commonly used. In an external magnetic field, the spins align with the field lines and precess at a certain frequency, namely the Larmor frequency. As a result, a longitude magnetization appears. This magnetization can be tilted into the transverse plane through a radio frequency pulse (RF-pulse). The MR signal is then measured as an echo of the free induction decay of the transversal magnetization (Haacke et al. 1999).

Spatial encoding of the MRI-Signal is realized adding magnetic gradients to the external magnetic field. As a result, the Larmor-Frequency varies whereby the spins become dephased. The gradients are applied several times with variable strength to generate various dephasing. As a consequence, the resulting MR signal is composed of different spatial frequencies. The intensities of these frequencies are collected in the so called k-space which is connected with the final image via Fourier-transform. A single data point in the k-space contains information about all pixels in the final image. Therefore, the size of the k-space determines the size and resolution of the final image.

There are several strategies to excite and capture all required frequencies of the k-Space in an MRI-measurement. Robust single point imaging (SPI) methods require long measurement times, whereas rapid single shot measurements are prone to flow induced image artefacts. Therefore, most medical examinations use Cartesian line-wise sampling as a compromise of measurement time and measurement quality. Cartesian measured k-Space is easily transformed into the final image using a Fast-Fourier-Transform. In contrast, k-space data from non-Cartesian trajectories such as radial or spiral sampling require additional post processing steps to transform the non-linear data onto a Cartesian grid. As an advantage, radial sampling is less prone to flow-induced image artefacts such as blurred images caused by flow turbulence (Bernstein et al. 2004).

Regardless whether Cartesian or radial sampling is used, acquisition times of conventional MRI-measurements are about 1 second for a two dimensional image. In velocity sensitive measurements, frame rate increases due to additional encoding steps. For this reason, conventional MRI is not suitable for time resolved measurements in many fluid flows because of insufficient temporal resolution.

Time-resolved sequence design

As described before, the acquisition time in MRI is depending on the number of encoding steps. Therefore, the basic idea to reduce acquisition time is to under-sampled the k-space. Untenberger et al. (2016) propose a method based on this concept for time-resolved flow measurements in medical examination using a radial sampling pattern. In contrast to Cartesian sampling, an inherent feature of these non-linear sampling is a high sampling density in and around the k-space center while the outer regions of k-space are sampled at lower densities. Furthermore, under-sampling these non-linear acquisition causes noise-like artefacts which are removed using an iterative reconstruction algorithm.

Under-sampling of radial sequences is easily implemented by measuring only a few spokes, rather than the total amount required for a full scan. In contrast to Untenberger et al. (2016), this study uses a full radial acquisition instead of asymmetric sampling. The basic layout of the sequence is depicted in Fig. 1. A conventional fully-sampled radial sequence is used to validate the results obtained from the time-resolved measurements. The conventional one-component (1C) velocity sensitive sequence captures 201 spokes at an acquisition time of 1.3 seconds per image. In contrast, the implemented under-sampled sequence samples only 9 spokes which increases the frame rate to 16.4 Hz. With the same approach, time-resolved measurements of proton density distribution without velocity encoding are performed at a frame rate of 41 Hz. The sequences were programmed with the sequence prototyping framework pulseq (Layton et al. 2017).

Image artefacts caused by under-sampling are reduced in post processing using an iterative reconstruction algorithm adapted from Lustig et al. (2007). They proposed a method to highly under-sample conventional MRI measurements in order to shorten acquisition time in medical diagnostic. In addition, this method is extended with suggestions for non-medical flow measurement proposed by Holland et al. (2010). All data processing including the sequence design, image reconstruction and flow visualization are performed using MATLAB (The Mathworks, Natick, MA).

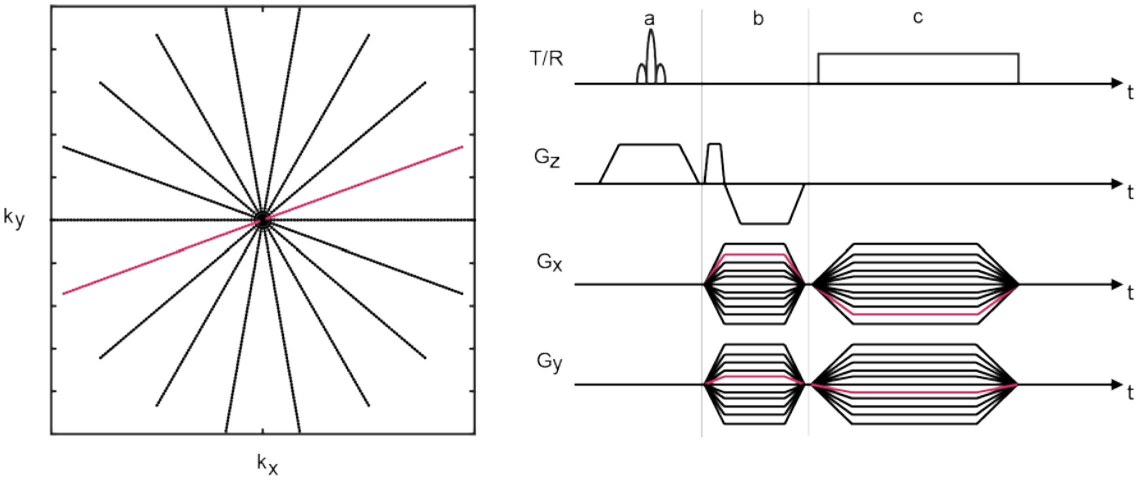

Fig 1: Sampling trajectories (left) and layout of a time-resolved, 1C velocity sensitive MRI-sequence (right) with events for transmitter and receiver (T/R) and magnetic gradients (G_x, G_y, G_z): a) slice selection, b) rephrasing with velocity encoding (G_z) and prephasing events, c) readout gradients and data acquisition. Prephasing and readout gradients (G_x, G_y) are changed in every repetition of the sequence in order to measure different spokes through k-space. Red lines indicate a pair of gradients and the associated spoke.

Experimental Set-Up

Measurements are performed on a 3 Tesla whole-body MRI scanner, a MAGNETOM Trio by Siemens, with gradient amplitude 38 mT/M and gradient slew rate 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 scanners usually used in clinical applications, this laboratory is specifically designed for fluid mechanics applications. MR signal was measured either with two 8-channel body matrix coils or with a 1-channel head coil.

A 10 m long horizontal pipe with water and air is placed through the bore of the MRI scanner. The pipe is connected to a pump system capable of 300 Liter per minute and a tank capacity of 1000 Liter. The flow medium is purified water with 1 mg per Liter of Copper Sulphate as a contrast agent. To create a transient multi-phase flow, compressed air is added through a pressure regulator. The experimental set-up is pictured in Fig. 2. Flow characteristics of the multi-phase flow are shown in Fig 3.

Fig 2: Pictures of the experimental set-up. A straight pipe, shown on both image parts, connects the pump system with the flow model in the MRI system.

Fig 3: Picture of the two-phase flow experiment with 1-channel head coil for MRI-measurements.

Results

Experiments were done in a two-dimensional 128 mm x 128 mm FOV with 1 mm resolution. Each sequence was continuously played out resulting in a time series of measured data.

To validate the proposed method, a steady state pipe flow is measured with both the conventional and time-resolved sequence. Figure 4 shows the obtained velocity distributions of one measurement in a time series of 200 measurements. Pixels with magnitudes lower than 50% of the maximum magnitude are removed. The result of the conventional measurement shows a clear cut-off between flow and ambient air, whereas under-sampled measurement with a conventional reconstruction leads to significant artefacts outside of the flow. However, both show similar qualitative velocity distribution. In addition, iterative reconstruction removes the artefacts caused by under-sampling. As a result, almost the same image quality as a full measurement is obtained.

The resulting flow rate, which is calculated from the time series of velocity sensitive measurements, is depicted in Fig 5. The flow rate obtained with the conventional measurement is almost at a constant level of 38.7 Liter per minute. In contrast, the mean flow rate of the under-sampled measurement with conventional reconstruction is higher and the flow rate over time shows wider fluctuations. These fluctuations are reduced using the proposed iterative reconstruction. However, the resulting mean flow rate is about 4 % lower than the flow rate of the full measurement.

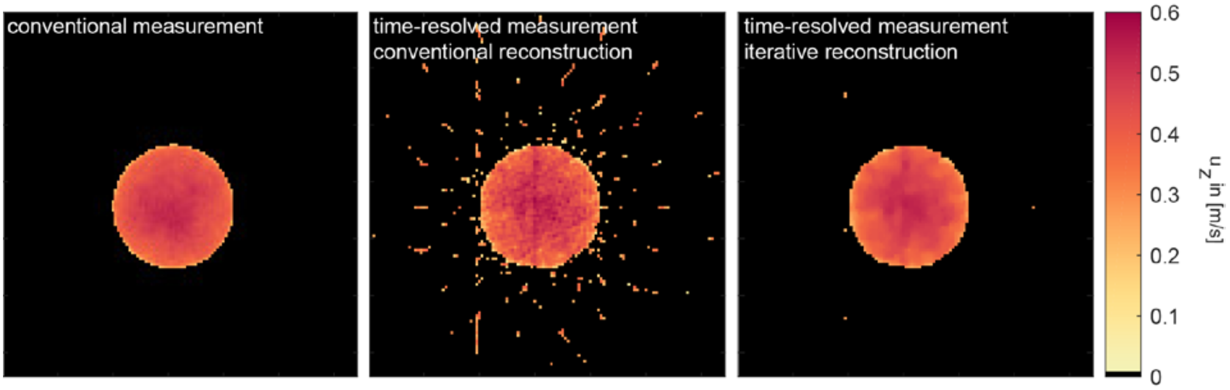

Fig 4: Results of the steady-state flow experiment with velocity encoding.

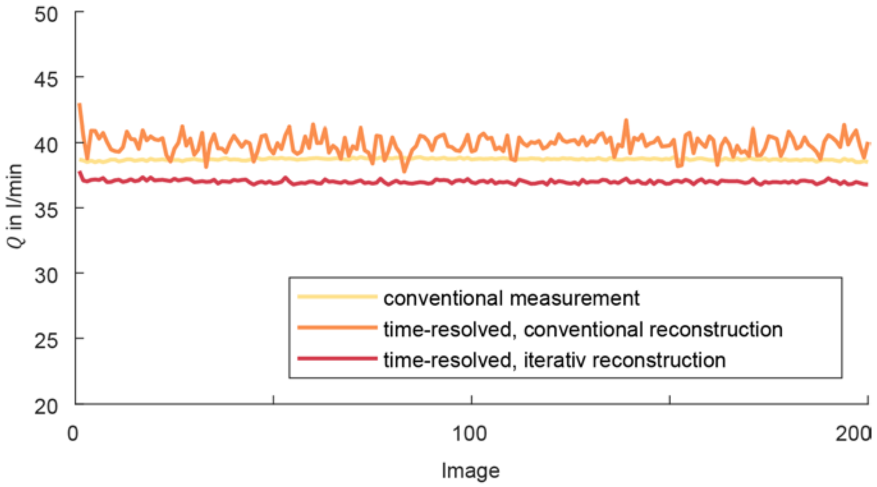

Fig 5: Flow rate of the steady-state flow over a time series of 200 images.

Conventional and iterative reconstructed results of the time-resolved measurement in the multiphase flow are pictured in Fig. 6. As only the water phase leads to high signal intensities, the changing water-levels are visible. Furthermore, the flow velocity in the water phase is displayed. It becomes clear that the water level and the maximum velocity changes drastically within only 180 ms. Thus, conventional MRI flow measurement would not be able to capture these flow characteristics due to long acquisition time. Conventional and iterative reconstructions of the time-resolved measurement show a similar qualitative velocity distribution inside the flow. Again, artefacts caused from under-sampling are removed using iterative reconstruction.

Further characteristics are obtained from the flow rate that is depicted in Fig 7. In contrast to the steady state flow, the flow rate is not constant and changes from 45 Liter per minute to 5 Liter per minute. In addition, this illustration also indicates that the investigated two-phase flow has a periodic character over some time periods.

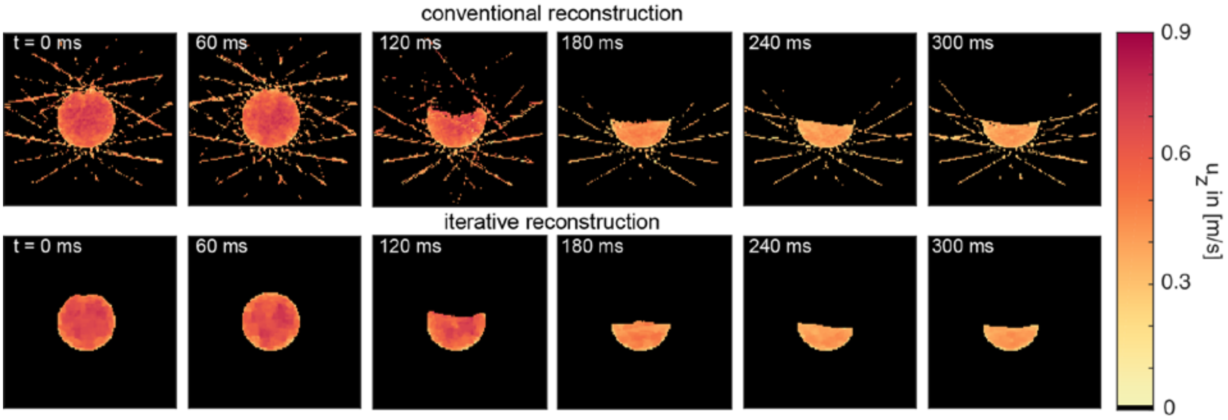

Fig 6: Results of the two-phase flow experiment with velocity-sensitive encoding.

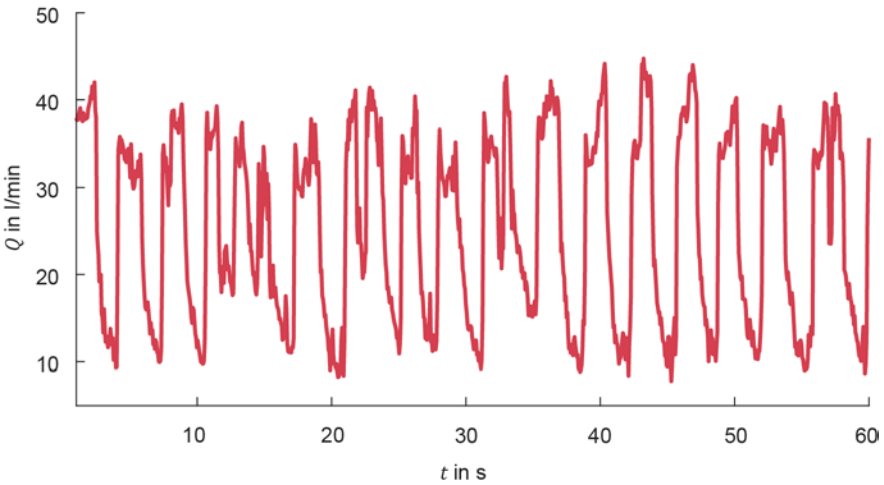

Fig 7: Flow rate of the two-phase flow calculated from a time series of 200 images.

Conclusion

Based on a transient water-air flow experiment, the application of time-resolved MRI-measurement in fluid dynamics application has been demonstrated. This measurement technique enables frame rates of up to 41 Hz for proton-density-weighted MRI and up to 16 Hz for velocity-sensitive MRI. This sequence can be applied to transient single-phase or multi-phase flows in which at least one fluid phase contains water protons.
A comparison with a conventional measurement in a steady-state flow showed that qualitative velocity distribution are captured correctly. Iterative reconstruction reduced artefacts from under-sampling. As a result, the obtained image quality was close to a conventional measurement. However, flow rate is decreased by about 4%. Further research is directed to improve the image reconstruction in order to minimize this deviation. Time-resolved measurements in the transient water-air flow seem reliable. Future studies will investigate approaches to validate this method.
A disadvantage of this method is the increasing post-processing time due to the iterative reconstruction. However, these time-resolved measurements were set up and completed within a few days. This underlines the benefits of MRI as a fast and efficient measurement technique for applications in the field of fluid dynamics. Future work will focus on 3C velocity-sensitive measurements as well as the improvement of image quality and higher frame rates.
The presentation at the meeting will discuss the implementation of time-resolved MRI-measurements for engineering applications as well as future research opportunities.

References

Bernstein, M. A., King, K. F., & Zhou, X. J., 2004: “Handbook of MRI pulse sequences”, Burlington MA Elsevier

Elkins, C. J., & Alley, M. T., 2007: “Magnetic resonance velocimetry: applications of magnetic resonance imaging in the measurement of fluid motion”, Experiments in Fluids, Vol. 43, No. 6, pp. 823-858

Freudenhammer, D., Baum, E., Peterson, B., Böhm, B., Jung, B., Grundmann, S., 2014: "Volumetric intake flow measurements of an IC engine using magnetic resonance velocimetry", Experiments in Fluids, Vol. 55, No. 5, pp. 1724

Gladden, L. F., Sederman, A. J., 2013: "Recent advances in flow MRI", Journal of Magnetic Resonance, Vol. 229, pp. 2-11

Haacke, E. M., Brown, R. W., Thompson, M. R., Venkatesan, R., 1999: "Magnetic resonance imaging: physical principles and sequence design", Vol. 82, New York:: Wiley-liss.

Layton, K.J., Kroboth, S., Jia, F., Littin, S., Yu, H., Leupold, J., Nielsen, J.F., Stöcker, T., Zaitsev, M., 2017: "Pulseq: A rapid and hardware-independent pulse sequence prototyping framework", Magnetic resonance in medicine, Vol 77, No. 4, pp. 1544-1552

Lustig, M., Donoho, D., Pauly, J. M., (2007): "Sparse MRI: The application of compressed sensing for rapid MR imaging", Magnetic resonance in medicine, Vol 58, No. 6, pp. 1182-1195.

Markl, M., Frydrychowicz, A., Kozerke, S., Hope, M., & Wieben, O., 2012: „4D flow MRI”, Journal of Magnetic Resonance Imaging, Vol. 36, No. 5, pp. 1015-1036.

Untenberger, M., Tan, Z., Voit, D., Joseph, A. A., Roeloffs, V., Merboldt, K. D., ... & Frahm, J, 2016: "Advances in real-time phase-contrast flow MRI using asymmetric radial gradient echoes”, Magnetic resonance in medicine, Vol. 75, No. 5, pp. 1901-1908.

Karlsruhe, Germany, ISBN 978-3-9816764-5-7