Measuring Turbulent Swirling Flow with Phase-Contrast MRI

M. Bruschewski[1,*], H.-P. Schiffer[1], S. Grundmann[2]

1: Institute of Gas Turbines and Aerospace Propulsion, Technische Universität Darmstadt, Germany
2: Center of Smart Interfaces, Technische Universität Darmstadt, Germany
* correspondent author: bruschewski@glr.tu-darmstadt.de

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Phase-Contrast Magnetic Resonance Imaging (PC-MRI) has proven to be a versatile tool to investigate the inner structure of flows in the human body. Very recently, it has found its way to engineering (see Elkins and Alley 2007). PC-MRI is comfortable to operate: It does not require any optical access, it is non-invasive and it is fast. Using rapid prototyping as manufacturing process, the full process from model construction to post-processing of the data is manageable in just under a week. Despite its huge benefits, the question remains if PC-MRI can compete in terms of accuracy and image quality.

Swirling flow is the ultimate test case for both experimental and numerical methods. It combines steep gradients of static pressure and velocity with recirculation, turbulence and instability. It is found in a broad range of industrial devices, including combustion chambers, particle separators, swirl-flow cooling and other fluidic appliances. Although this equipment has been around for decades, the mechanism behind the flow structure is far from being fully understood. The complexity and difficulty to model this type of flow have led to an extensive research on this topic (see Hogg and Leschziner 1989 and Jarkirlic et al. 2002).

Because of these reasons, we have set our task to investigate the applicability of PC-MRI towards the measuring of strongly turbulent swirling flow. The reference data for verification is provided by Laser Doppler Anemometry (LDA).

The investigated flow system consists of a circular channel of 44 mm diameter which is attached to a tangential-type swirl generator with two quadratic inlet passages. The length of the channel is 10 diameters after which the fluid exits into a plenum. As flow medium deionized water with a low concentration of Gadolinium-based MRI contrast agent is used. The study encompasses the combinations of three different swirl intensities (S = 1, 3, 5) and three different Reynolds numbers (Re = 2000, 8000, 32000). The values were selected with the intention to represent the common range from technical devices and former studies (e.g. Grundmann et al. 2012). It is shown that the measuring of swirling flow is generally possible, although there are discrepancies in the results for higher Reynolds and swirl numbers. There are three major outcomes of this study:

(1) The MRI acquisitions of swirling flow are corrupted by at least two additional artifacts that are usually not significant in non-swirling flow. These are the misregistration of the signal location manifested in an oval deformation of the otherwise helical flow, and secondly, the velocity misinterpretation by acceleration due to the circular motion. The degree of error is almost non-existent for low Reynolds and swirl numbers but increases as both numbers increase.
(2) The signal-to-noise ratio (SNR) as the common measure of image quality does not reflect the impact of Reynolds and swirl number on accuracy. SNR should therefore not be used to report the uncertainty of the measured velocity.
(3) Decreasing echo time is beneficial for the reduction of flow related artifacts. However, this measure must be compensated by a stronger field gradient which leads to more pronounced eddy current effects. Eddy currents are correlated which makes it possible to compensate the error via reference scans. Therefore, it is proposed to decrease echo time while increasing gradient strength and performing reference scans.

It can be concluded that PC-MRI is accurate for low to medium Reynolds and swirl numbers (in respect of the investigated range).

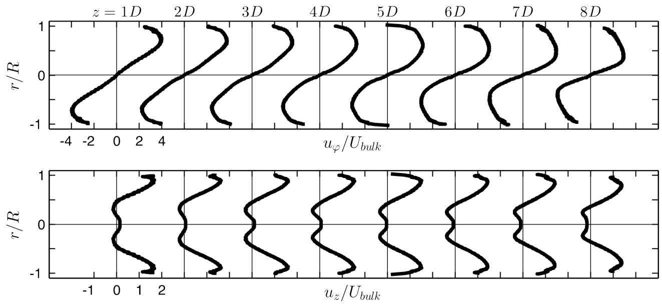

Fig. 1 Main velocity components for a selected configuration (PC-MRI).

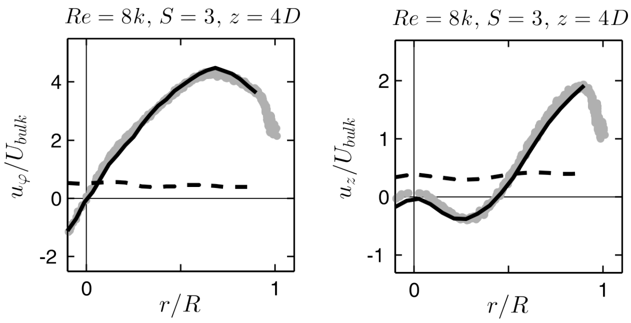

Fig. 2 Comparison between LDA and PC-MRI for a selected configuration. The gray lines represent the circumferentially averaged velocity profiles from PC-MRI. The solid black lines denote the LDA data and the dashed lines represent the corresponding RMS values from the LDA measurements.

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