Measurement Errors in Magnetic Resonance Imaging of Fluid Flows
Flow Visualization with MRI
from Medicine to Engineering
Flow Visualization with MRI
from Medicine to Engineering
Our Niche

MRI in Medicine

<100 researchers world wide

Fluid Mechanics

Interval Methods
Today's Agenda

1. MRI principles
2. MRI in Fluid Mechanics
3. MRI Flow Lab
4. Measurement Errors in MRI
Today's Agenda

1. MRI principles
2. MRI in Fluid Mechanics
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Theoretical Background

1. MRI Principles

The spin

- quantum mechanical property
- the spins align with field lines
- not stationary: precession motion
- precession frequency depends on field strength:

\[ \omega = \gamma B \]

Larmor frequency:

- local field strength
- gyromagnetic ratio
Basics of MR Imaging

1. MRI Principles

\[ \omega = \gamma (B_o + \Delta B) \]

**gyromagnetic ratio**

High field

Low field
Measuring Flow Velocity

1. MRI Principles

Magnetic gradient over time

Fluid particle

High field

Low field

$B_0$
Measuring Flow Velocity

1. MRI Principles

Magnetic gradient over time

\[ \omega = \gamma B \]
Measuring Flow Velocity

1. MRI Principles

Linear relationship between residual phase angle and velocity
Possibilities and Constraints in MRI

1. MRI Principles

Possibilities

1. No optical access needed
2. Full 3D measurements within minutes
3. Simple post-processing (FFT)
4. Simultaneous measurement of fluid velocities and flow geometry.
1. MRI Principles

Constraints

1. Danger because of magnetic field

2. Restrictions in materials
   - Model materials must be non-ferrous
   - Better no metals at all (antenna!)
   - Materials must have similar magnetic properties as the fluid, otherwise image distortions

3. Working fluid must have measurable spin, e.g. water

Most suitable material combination:
Water + PMMA, POM, PA, …

Not suitable:
Air, Metals, …
1. MRI Principles

Constraints

4. Low temporal resolution compared to other measurement techniques

5. Relative new to engineering: not yet established in industry, only in academics
Today’s Agenda

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Conventional Experiments vs. MRI

2. MRI in Fluid Mechanics

Probes

Laser-optical instruments

Flow MRI

Engine-realistic experiments

Engine-realistic experiments possible

Quick simplified experiments

Source: biomec.io, Elkins&Alley 2007
Improving Flow Designs with MRI

2. MRI in Fluid Mechanics

Conventional design process

Future?

system test

system test

design revisions

validation by MRI

validation by MRI

numerical layout

numerical layout

numerical layout

numerical layout

design revisions

numerical layout

validation by MRI

validation by MRI

numerical layout

validation by MRI

validation by MRI

validation by MRI

design revisions

design revisions

system test

system test
Implementation of MRI in Actual Design Processes

2. MRI in Fluid Mechanics
Implementation of MRI in Actual Design Processes

2. MRI in Fluid Mechanics

Turbine blade cooling

< 5 days
Flow Analysis with MRI

2. MRI in Fluid Mechanics

Nuclear fuel bundle model

- (0.8 mm)$^3$ resolution
- 9 Mio. velocity vectors
- 3 h measurement time
Flow Analysis with MRI

2. MRI in Fluid Mechanics

Periodic valve flow in IC engine models

- (1.6 mm)$^3$ resolution
- 3 Mio. velocity vectors
- 1 h measurement time
Today's Agenda

1. MRI principles
2. MRI in Fluid Mechanics
3. MRI Flow Lab
A Dedicated Lab for Engineering

3. MRI Flow Lab

2012 – 2016: Precursory experiments at the University of Freiburg
A Dedicated Lab for Engineering

3. MRI Flow Lab

2012 – 2016: Precursory experiments at the University of Freiburg
Dec 2016: Approval and Funding
A Dedicated Lab for Engineering

3. MRI Flow Lab

2012 – 2016: Precursory experiments at the University of Freiburg
Dec 2016: Approval and Funding
Jan 2018: Completion of the laboratory
Design Features

3. MRI Flow Lab

Examination room

3T whole-body MRI scanner (Trio, Siemens)
Design Features

3. MRI Flow Lab

Examination room

- ceiling rail system
- 6 filter panels
- sealed floor
Flow Loop Installation

3. MRI Flow Lab

Preliminary flow loop (200 L/min)
Today's Agenda

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Systematic Measurement Errors

4. Measurement Errors in MRI

Example: flow induced misregistration

Conventional MRI sequence:

RF
Gz
Gy
Gx
T

Fluid particle path:

1 m/s flow velocity and 2 ms encoding delay → 2 mm misregistration
Systematic Measurement Errors

4. Measurement Errors in MRI

Manifestation of misregistration

- **Example**: Circular motion

Removing misregistration by synchronizing all encoding events
4. Measurement Errors in MRI

Experimental confirmation

- Swirl flow test case

Conventional MRI

Improved Sequence

Flow off

2 m/s fluid rotation

$T_{E_x} < T_{E_y}$

4 m/s fluid rotation

$T_{E_x} < T_{E_y}$
Experimental Confirmation

• Flow contraction test case
Pulse Sequence Design – Better Accuracy

4. Measurement Errors in MRI

Experimental Confirmation
- Flow contraction test case

![Comparison of conventional MRI and improved sequence](image-url)
Pulse Sequence Design – Better Accuracy

4. Measurement Errors in MRI

Experimental Confirmation
• Flow contraction test case

![Diagram showing flow contraction test case and comparison between conventional MRV and improved sequence]
Thank You