Velocimetry Using Magnetic Particles

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Abstract

Foundational experimental results are presented to sense the motion of magnetic particles inside opaque containers as an alternative to conventional optical methods and expensive X-ray techniques. Commercially-obtained 3-axis magnetic sensors were used to measure the magnetic field emitted from magnetic spherical particle. After calibrating on all three axes, the sensors were positioned to surround a particle being monitored. To examine the effects materials in screening out the magnetic field, we examined the effects of different containers: aluminum, two varieties of stainless steel, and carbon steel. We also performed a test where we dropped a magnetic sphere into a cylinder filled with poly(propylene glycol), and used this date to measure the viscosity of the fluid.

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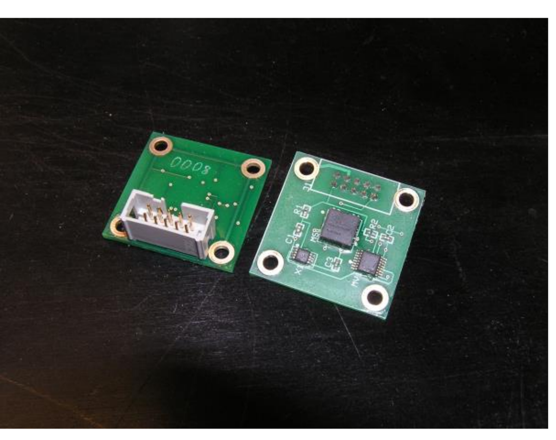
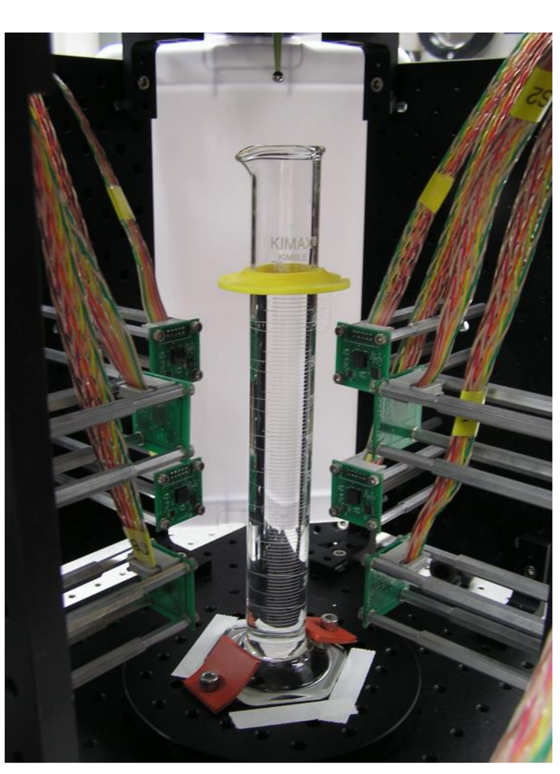




Introduction

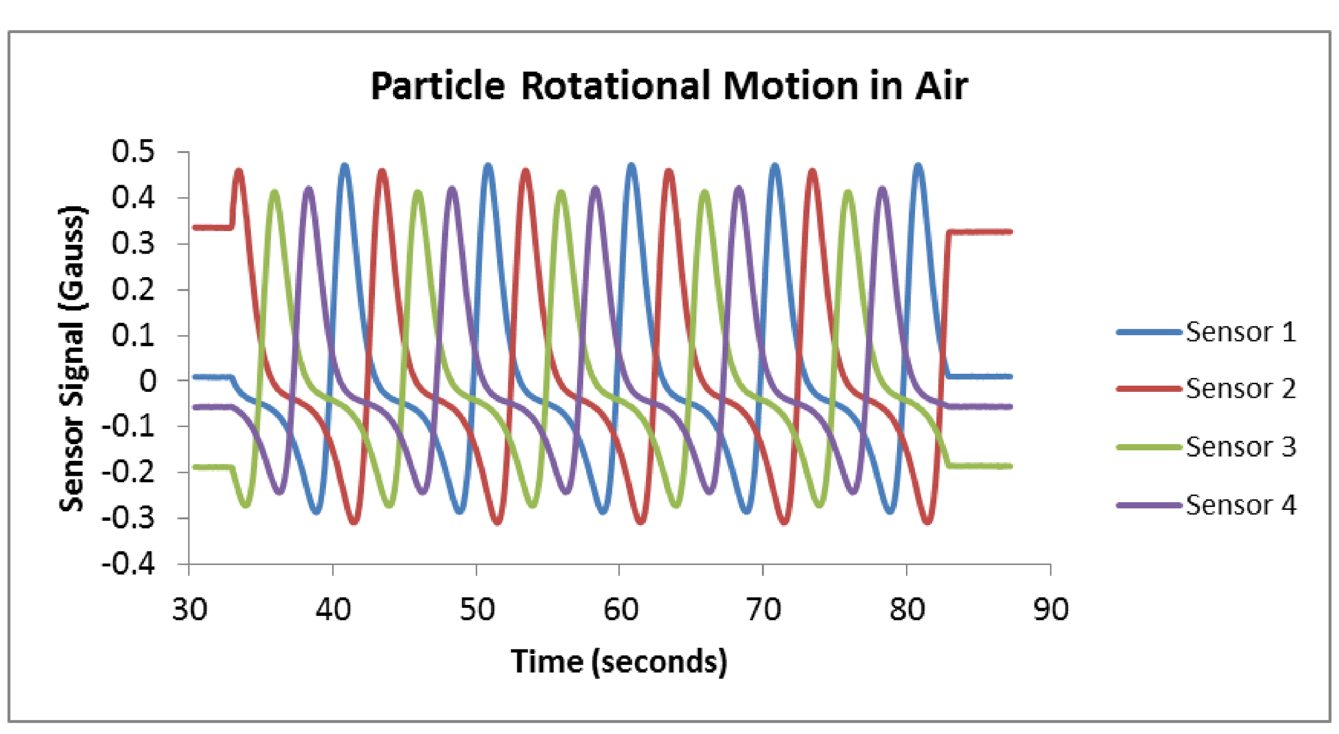
Currently, the detection of objects and fluid motion inside closed containers is challenging: in most applications, these containers are opaque. For this reason, optics cannot be used to see inside of the containers. X-ray detection can be used, but that method requires large, expensive equipment, and containers made out of materials with high atomic numbers shield x-rays. A relatively new technology may be able to replace these impractical methods: magnetic sensing. Magnetic particles produce a magnetic field, which can be measured using low-field sensing sensors. Magnetic fields are able to pass through nearly every material, and the sensors can measure very low field strengths. These sensors are extremely portable and relatively inexpensive, making them the perfect choice for many applications.

Sensors and Characterization

- Honeywell HMC1053 three-axis magnetic sensors were purchased and mounted to circuit boards, which were then connected to a data acquisition box using twisted-pair flat ribbon cables.
- Calibration
  - Placed sensors in calibrated Helmholtz coils to measure the sensitivity of the 3 axes (A-B-C) to a known magnetic field.
  - Each sensor has slightly different sensitivities (vary +/- 2.2%)
  - For a given sensor, the A&B axes had similar sensitivities (+/- 4.7% variation).
  - Using different ribbon cables or DAQ channels had minimal variation (+/-0.4%)
  - To account for these variations, we will use the unique sensitivities determined for each sensor axis.

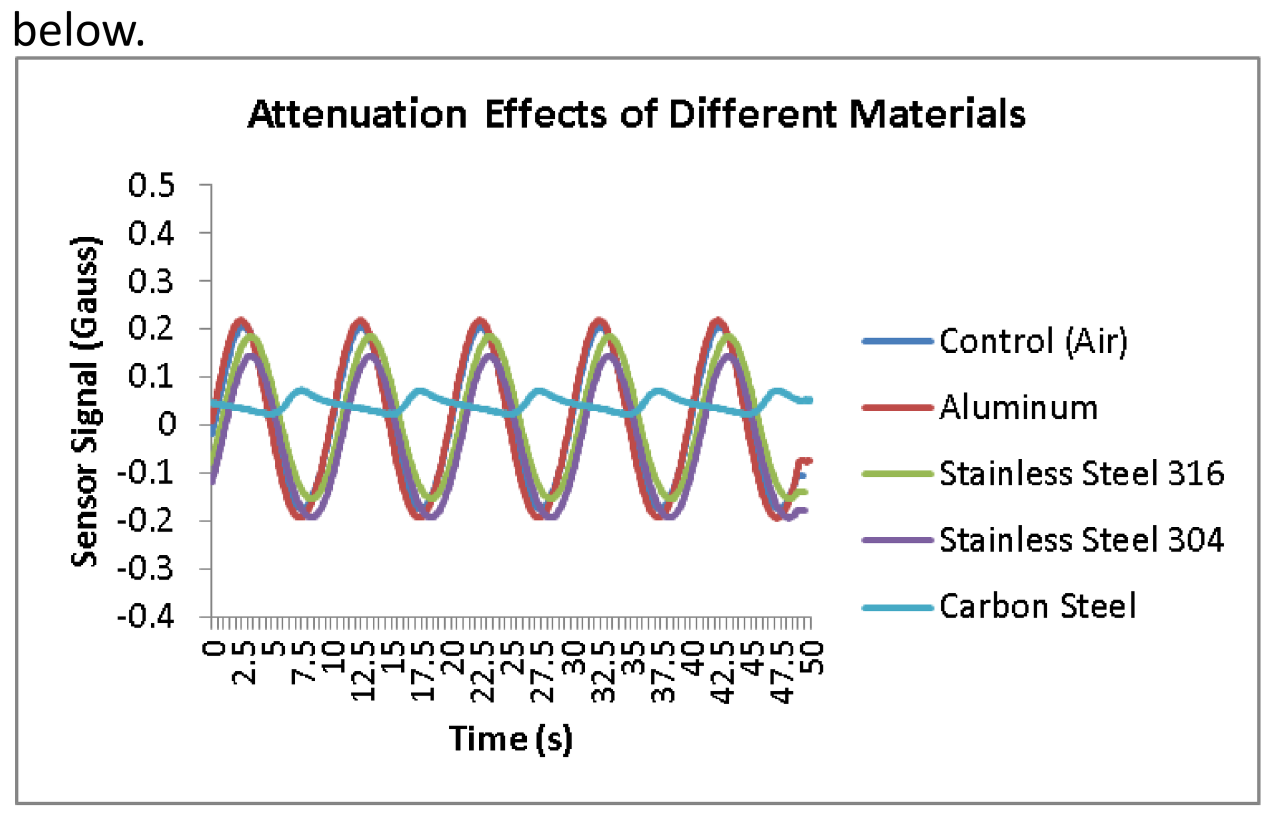
General Particle Motion

- The sensors were installed in the setup pictured to the left; five sensors (four along the X-Y plane and a fifth pointing down the Z-axis) were placed around a stage rotated using a motor. A magnetic particle was placed on a post on the stage.
- After the calibration process was complete, a procedure was developed to trace the movement of a 3/16" diameter magnetic particle in the rotational setup.
  - After the sensors are installed, a set/reset pulse is sent to ensure correct sensor polarity
  - The baseline signal from the sensors was zeroed to offset any rogue magnetic fields
  - The magnetic sphere is then installed and rotated five times at a fixed velocity
  - After rotation is complete, the sphere is removed to confirm that the baseline returns to zero



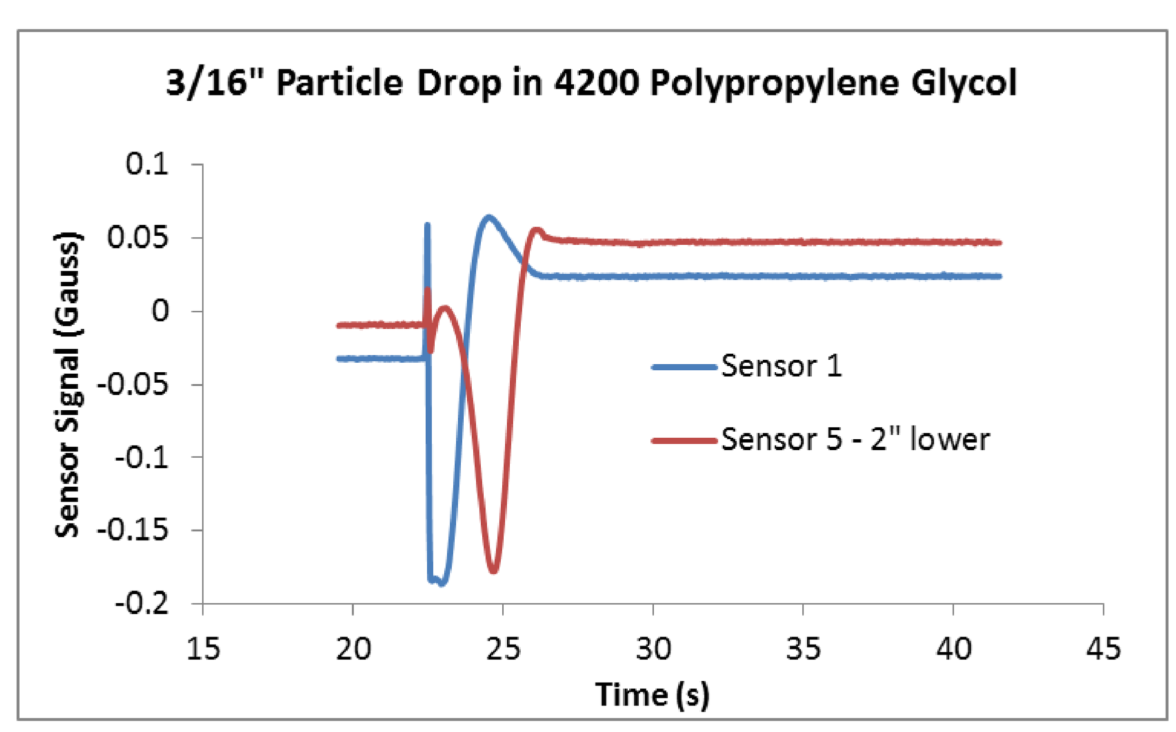
Shielding Effects of Different Materials

- In order to determine how the properties of different materials affect the sensor output signals, pipes of different materials were placed around the rotating particle.
- Pipes used: 150mm long, 89mm OD, and 5.5mm thick 304 stainless steel, 316 stainless steel, carbon steel, and aluminum
- Aluminum and stainless steel 316, which have no ferromagnetic properties, did not noticeably shield the particle's magnetic field. Stainless steel 304 shielded the field somewhat, but carbon steel provided the biggest interference of magnetic fields, as demonstrated in the chart below.



Determining the Viscosity of a Newtonian Fluid

- When a particle of diameter D is dropped into a Newtonian fluid, it experiences a drag force that can be calculated using the following equation: $F_{drag} = 3\pi\mu DU$, where μ is the viscosity of the fluid and U is the velocity of the particle in the fluid.
- The drag force is balance by the buoyancy force on the particle: $F_{buoyancy} = \frac{\pi D^3 \Delta\rho g}{6}$, where g is gravitational acceleration and ρ is the density of the fluid. When the terminal velocity of the particle in the Newtonian fluid is reached, the buoyancy and drag forces are equal to each other.
- Using the above principle, the viscosity of a fluid can be calculated if the velocity of the particle sinking in the fluid is known.
- A magnetic particle was dropped into a graduated cylinder filled with different fluids: water and 4200 or 12200 polypropylene glycol. With eight sensors – two on each side surrounding the cylinder – placed around the graduated cylinder, the movement of the particle was traced as it fell through the liquid.
- The calculated viscosity was , on average, 11.2% lower than the viscosity of the fluid measured by a TA Instruments AR-G2 rheometer.



Summary

- Established a working magnetic sensor array system for tracking particle motions
- Demonstrated we can magnetically sense through Al and SS316 with minimal interference
- Measured sphere migration in viscous fluid and calculated a viscosity within 15%

Next Steps

- Decrease particle size and examine sensor sensitivity limits
- Examine multiple particles and increase the number of sensors
- Develop inversion schemes to track multiple particles and ensembles of particles

Acknowledgements

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