Harmonic coil measurement system using a PCB coil

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Project background

- ISIS has limited capability to measure the magnetic field properties of our magnets. We currently rely on:
  - Magnetic simulations
  - Measurements carried out by magnet suppliers

- Commercial harmonic coil systems can be purchased at high cost. The challenge was to develop a system in house.

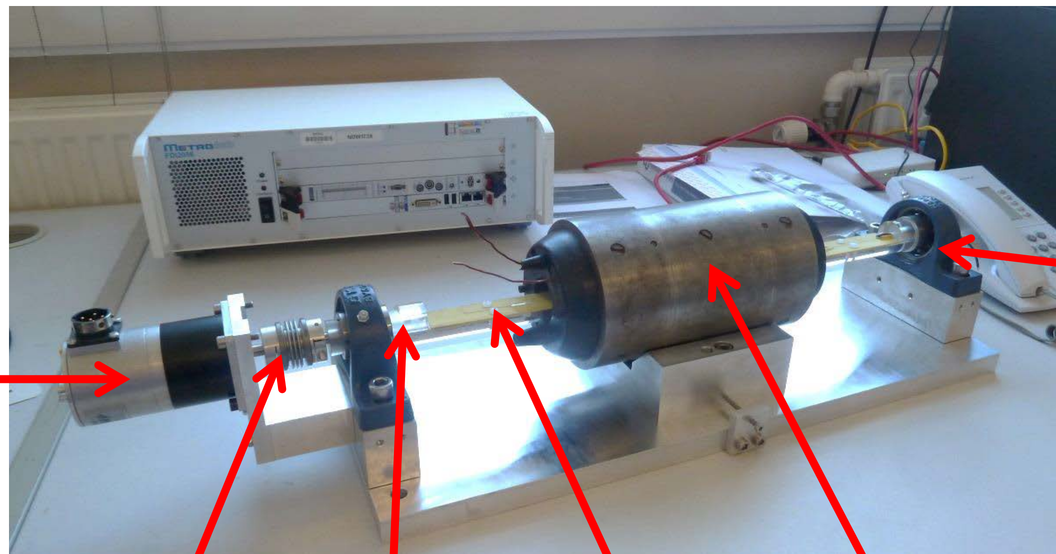
- Capability to measure magnets will come increasingly important for future upgrade and refurbishment projects

Objectives

- Develop a harmonic coil system suitable for measuring magnets with cylindrical symmetry
- Focus on mechanical system
  - Digital integrator can be purchased, which comes with software to log data and carry out basic analysis
- PCB coil used for simplicity/cost
  - Many manufacturers available
  - Easy to make a reasonable radial coil
- **First phase of project to test a simple rig as a proof of principle**

Measurement rig

- Metrolab FDI2056 integrator purchased for £18000
- Initial rig manufactured for <£1000



Stepper motor and encoder

Bellows flexible coupling

Acrylic rod for mounting PCB

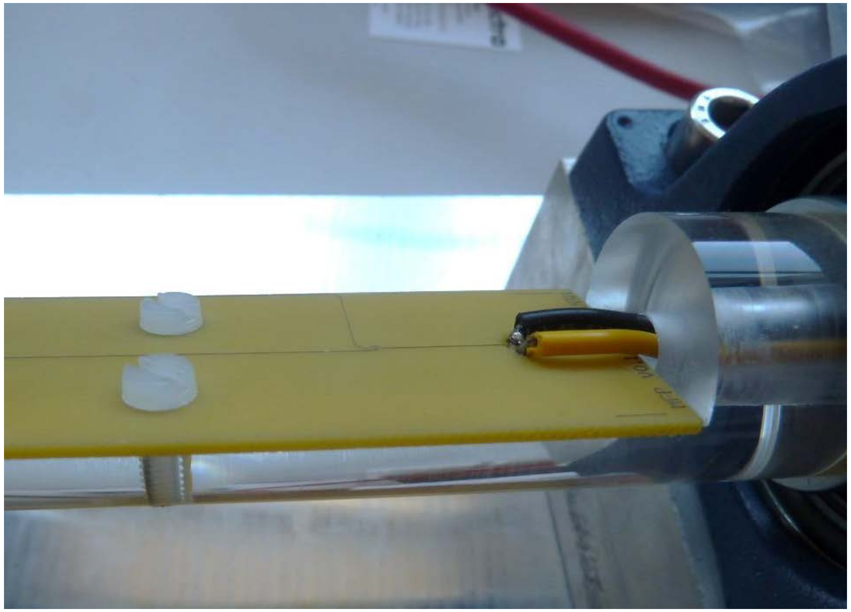
PCB coil

Test magnet

Ball bearings support rod at either end

PCB coil

- Double layer PCB with one turn per layer
- Coil 380mm long, 16mm radius, 2 turns
- Can fix positions of wire relatively easily and cheaply
- Possible to easily produce more complex coil designs in future



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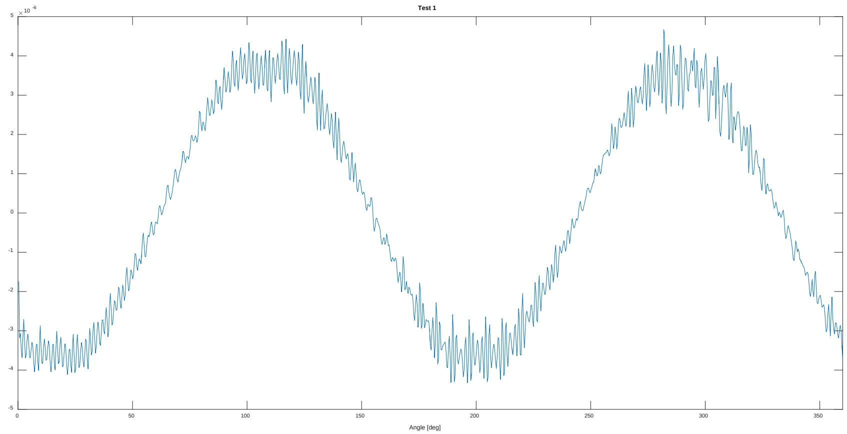
Initial testing

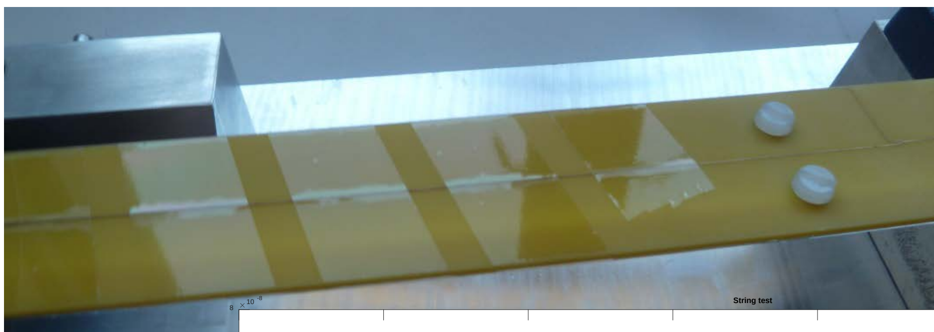
- Data from the first test had a significant component at $\sin 200\theta$
  - Stepper motor has 200 steps per revolution

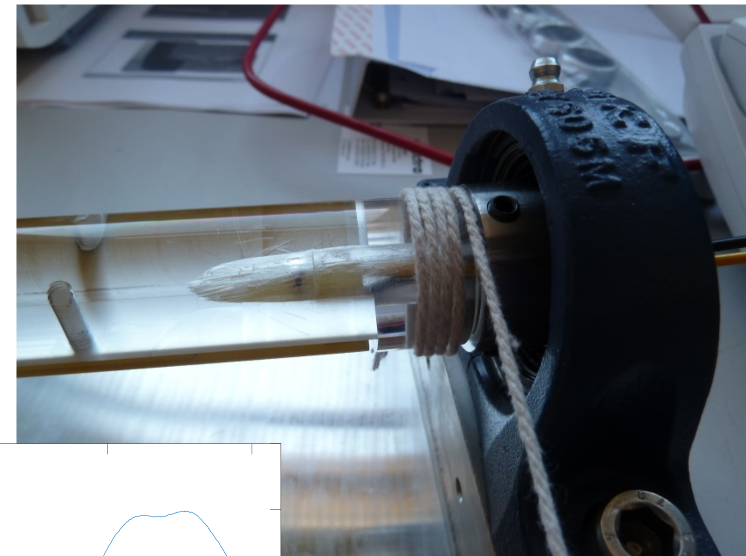


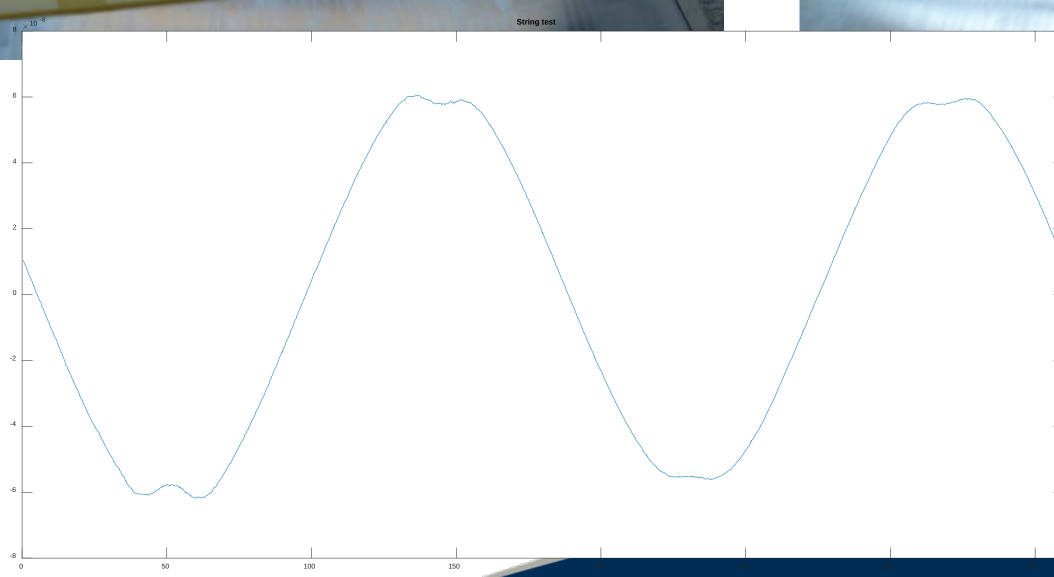
- As the PCB was only secured to the shaft at either end, it was able to vibrate, driven by the uneven drive from the stepper motor

Coil vibration

- String used as an alternative drive system
- PCB taped down to acrylic rod

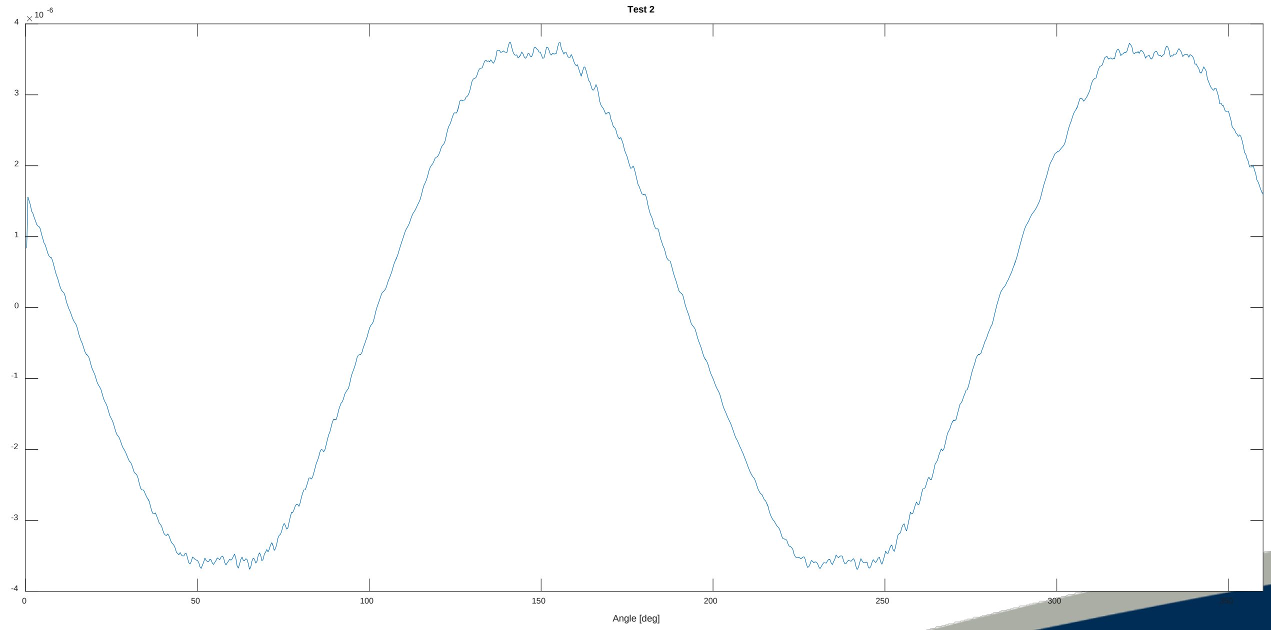






Coil vibration

- Could similar results also be achieved with the stepper motor?
  - Micro-stepping and different speed settings tried
  - Tripling the speed gave best results, but these still fell short of the string drive system



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Alignment of coil to magnet

- Offset quadrupole field causes a dipole field to be measured
  - Phase and magnitude of dipole field relative to starting position is converted into x and y displacements
  - Starting position of coil is known by taking an encoder reading when the coil is horizontal

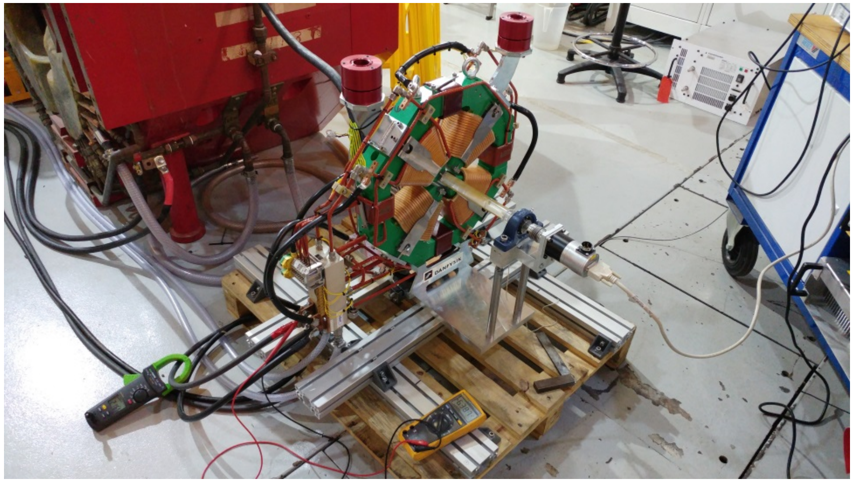
- It is possible the coil axis is not parallel to magnet axis
  - Axial alignment carried out by magnet geometry
  - Ideally would use coils to measure dipole field at either end of magnet

- Next phase of testing designed to allow improved alignment

Measuring a known magnet

- New magnets purchased for an upgrade project available and were measured by the supplier when they were manufactured

- Rig adapted to different magnet and to improve alignment



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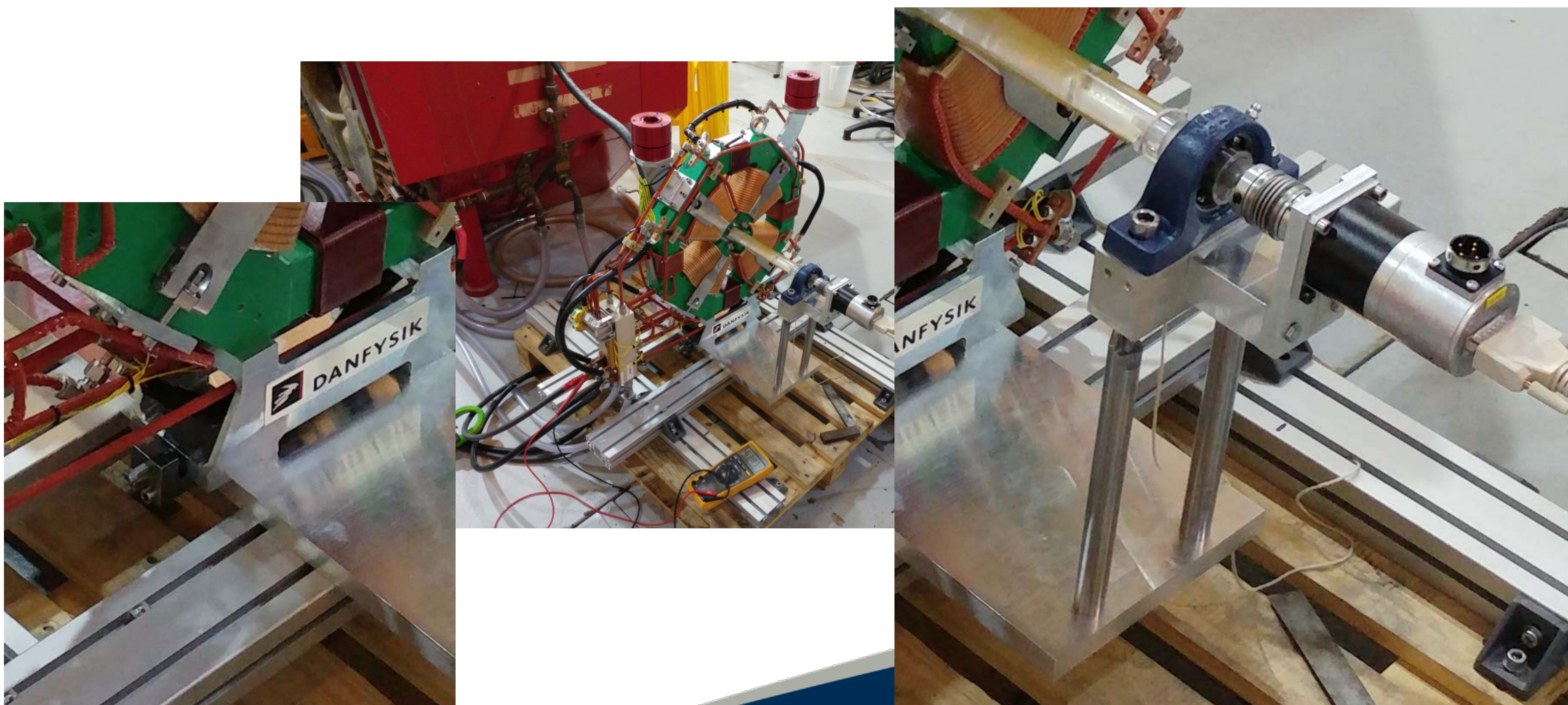
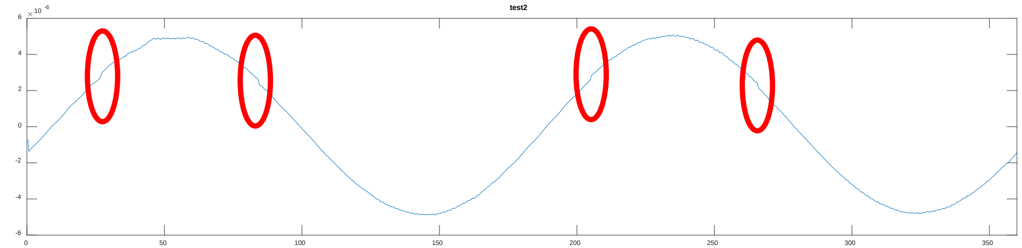
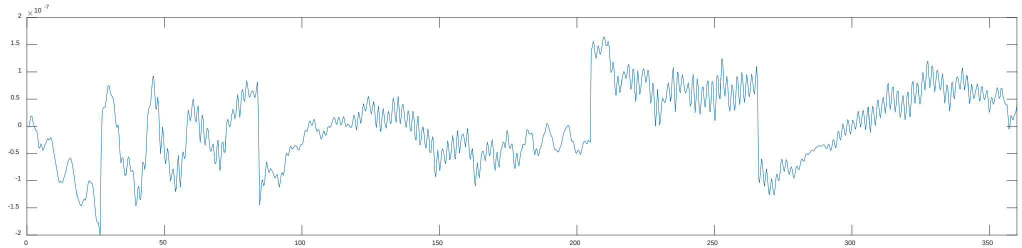


Integrator gain issues

Measured signal



Measured signal minus quadrupole harmonic



- Above a certain partial integral of flux there was an offset in the measured value
- This was eliminated by turning down the integrator gain from 10 to 4
- Caused by a known hardware bug which is being resolved

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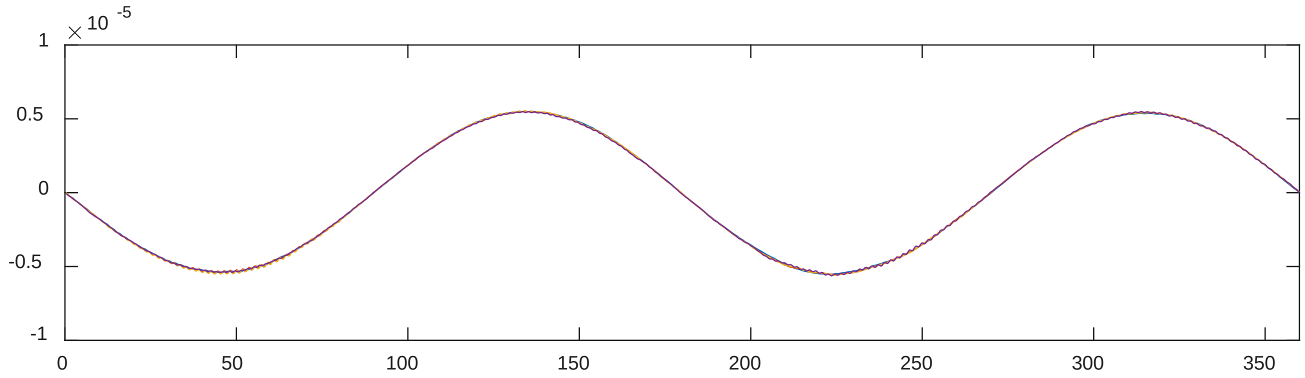
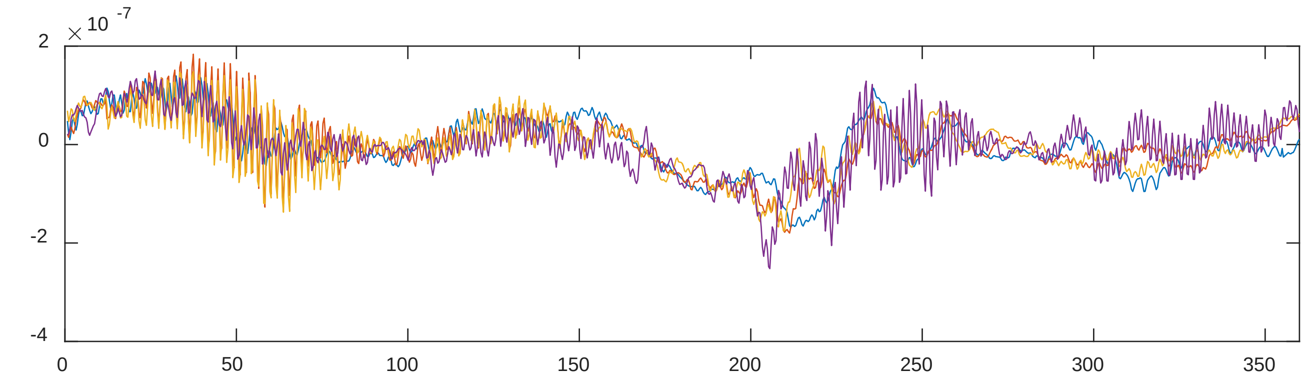
Results

Measured signal



Measured signal minus quadrupole harmonic



- Repeats show the same magnet measured four times without altering the setup

Field gradient

- **Measured integrated field gradient 3% higher than Danfysik's measurement**

- Further investigation found:
  - Two batches of magnet had been made
  - The first batch of magnets had been measured to have a 3% higher integrated field gradient than the second batch
  - Both batches were manufactured to the same standard, though a different batch of steel was used for the yokes
  - **The first batch of magnets had been measured using a rotating coil whereas the second batch of magnets had been measured using a stretched wire system**
  - Both batches of magnets had similar field gradients when measured using a hall probe

Differential shaft stiffness

- The shaft used to support the PCB is semi-circular

- Stiffness varies with orientation so the centre of the shaft oscillates up and down twice per revolution

- This induces skew dipole and sextupole terms

$$vs(\theta) = \frac{\cos 2\theta}{2} + \boldsymbol{\frac{d}{2}(\sin\theta - \sin 3\theta)}$$

The harmonic-coil method, L. Walckiers CERN 1992

- For a differential sag of 0.138mm this gives
  - $a_1 = \frac{d}{2} = 21.6$ units
  - $a_3 = -\frac{3d}{2} = -64.7$ units

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Quality of results

- Integrated field gradient accurate to 3% (probably better)
- Harmonics have limited accuracy
  - Most measured less than 10 units only the dipole and sextupole terms above 20 units
  - Dipole and sextupole components can be explained (to some extent)
  - Too much mechanical noise exists in the system
- With string drive system errors are smaller but no longer as repeatable

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Quality of results

5.3 Measurement of a quadrupole magnet

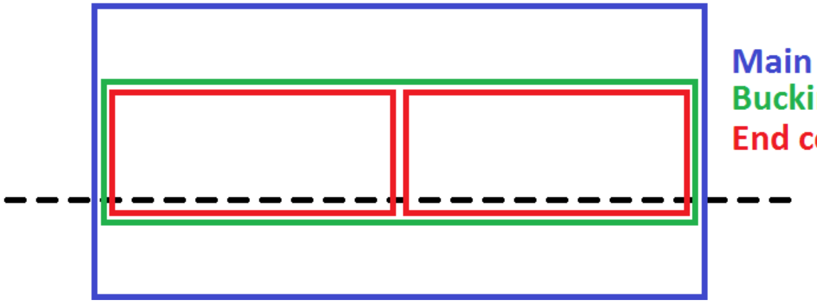
In a dipole magnet, a measuring coil displaced laterally or vertically will induce no voltage on the integrator connected to it. This is not true if higher harmonics are present or when a quadrupole or sextupole magnet has to be measured. A spurious signal therefore shows up if the assembly is such that the harmonic coil does not rotate in a perfect circle. Calculations show that without proper rejection of the main harmonic, it is hopeless to measure with high accuracy the field quality of a quadrupole.

The harmonic-coil method, L. Walckiers CERN 1992

- Many errors are related to the sensitivity of the coil to the main quadrupole field
  - Vibrations
  - Coil deflection

Planned developments

- Bucking coil to reject dipole and quadrupole harmonics



- Use a servo motor to give a smooth drive at constant speed
- Stiffer shaft with stiffness independent of orientation
  - Ceramic shaft
  - Sandwich PCB between two halves and glue together

Remnant field

- A side note on noise levels, the string drive test was carried out without the magnet being powered

- The remnant field is approximately two orders of magnitude weaker than the field when the magnet is powered

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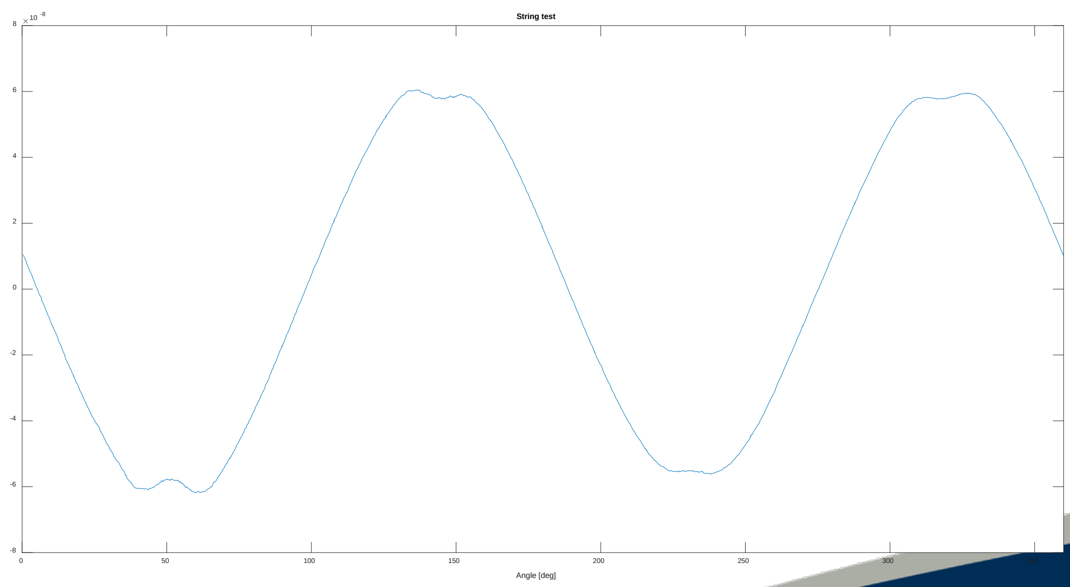

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Conclusions

- Developed a cheap harmonic coil system
- Improved understanding of the practical issues
- Found errors in the integrator and with magnet measurements done by manufacturer
- Can measure field gradient to a good level of accuracy
  - Planned work should enable the field quality to be measured to some accuracy

Acknowledgements

- Workshop for making the rig components
- Motion control group for help developing the drive system
- Martin Hughes for support with magnet testing
- Steve Jago and Iker Rodriguez for their support and advice

Thank you for your attention