Encoder-less rotating-coil acquisition

Piotr Rogacki[1], Lucio Fiscarelli[1], Stephan Russenschuck[1]

[1] European organization for nuclear research, CERN, Switzerland

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Rotating-coil measurements

- Standard measurement technique for fields of cylindrical symmetry represented in multipole expansion form:

$$B_y + iB_x = \sum_{n=1}^{\infty} \left(B_n(r_0) + iA_n(r_0)\right)\left(\frac{z}{r_0}\right)^{n-1}$$

- Measurement of flux by means of rotating rectangular coils. The expression for the flux intercepted by the coils:

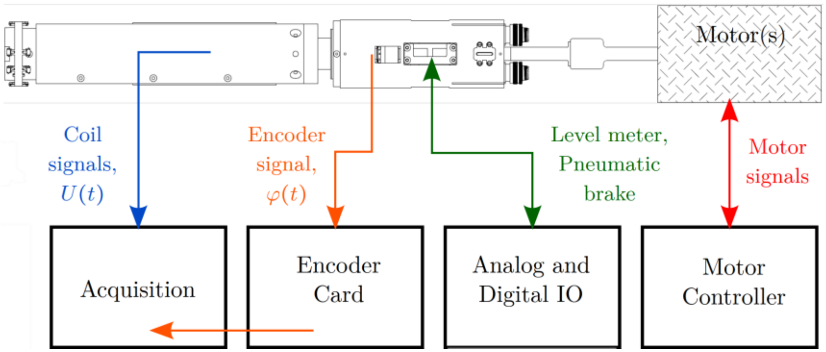
$$\Phi(\varphi) = \mathrm{Re}\left\{\sum_{n=1}^{\infty} S_n(B_n + iA_n)e^{in\varphi}\right\}$$

- B_n and A_n can be calculated from the Fourier coefficients (Ψn) of the measured fluxes:

$$B_n + iA_n = \frac{\Psi_n}{S_n}$$

S_n are the coil sensitivity coefficients, dependent on its geometry

- The flux is usually measured by integrating* the induced voltage between known angular positions (φ), provided by an encoder. This is an effective way of reducing the sensitivity to speed variations.



* Integration can be omitted in favor of voltage and speed measurement (see additional slides for details). This approach is also used in this presentation

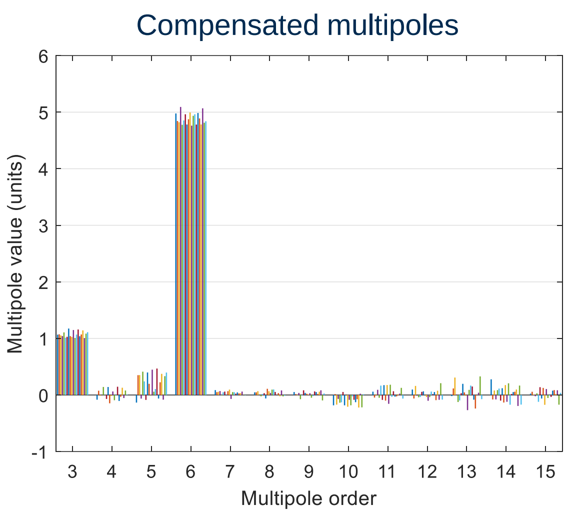
Encoder-**less** acquisition?

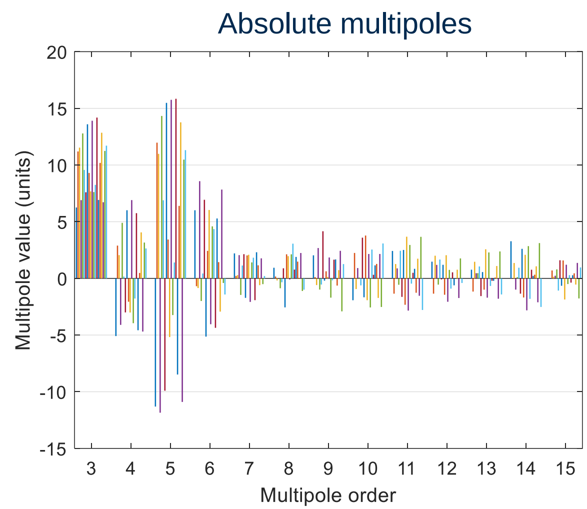
- Significant reduction of hardware complexity:
  - Optimization of costs and design constraints,
  - Improvement of speed and position measurements in long shafts and chains of shafts,
  - Enabling new approaches to rotating-coil system design.
- Challenge:
  - Position normally measured by encoder:

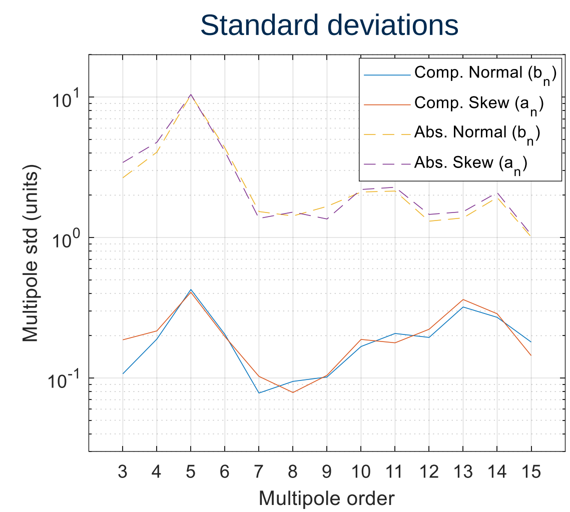
No position information and no correction for speed variation!

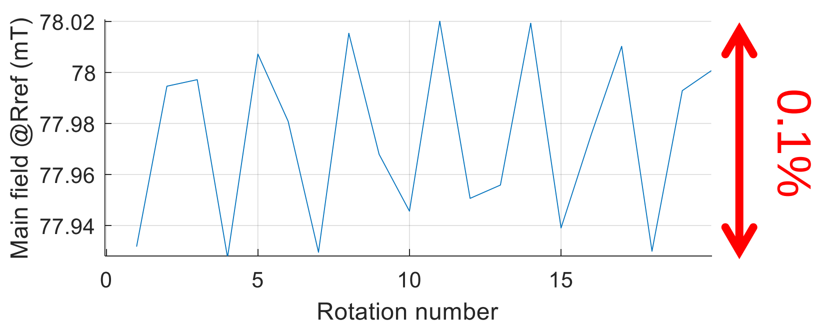
Effects on harmonics

- Even for relatively smooth rotation (approx. 3% speed variation) the error is non-negligible.
- Results below are assuming constant rotation speed (no knowledge of instantaneous position or speed)
- Compensation still helps significantly.







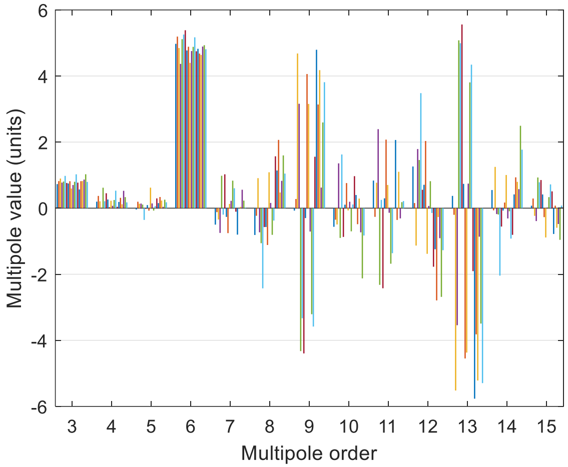


- Measurements in a quadrupole magnet; in the central, straight section of the field.
- Reference radius of 42 mm for the compensated arrangement, and 21 mm for the absolute coil (due to the use of intermediate coils).
- Main field of 78 mT at 21 mm.
- 20 rotations in total.

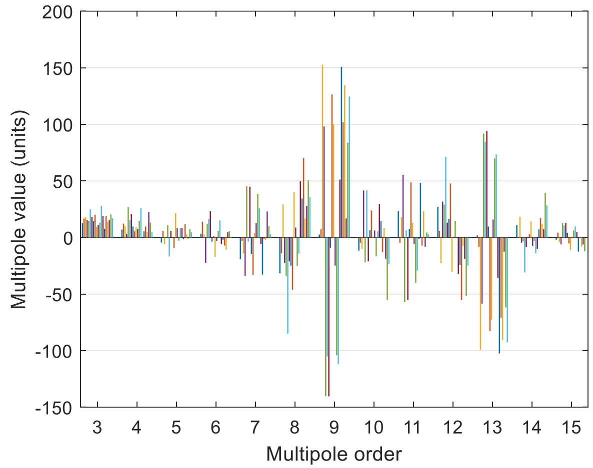
Effects on harmonics

- When speed variation is larger (>10%), effects are significantly stronger.
- Especially higher order multipoles are affected.

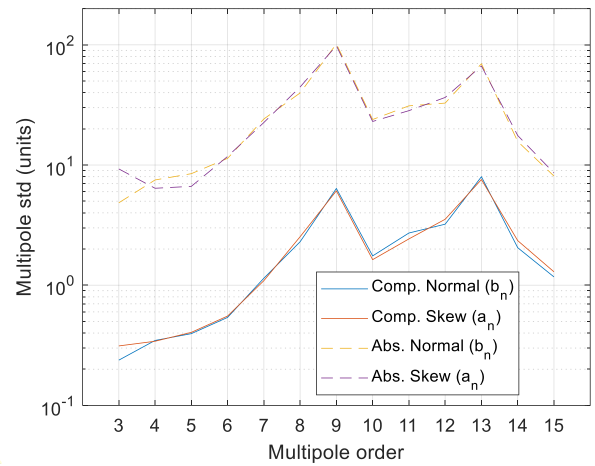
Compensated multipoles

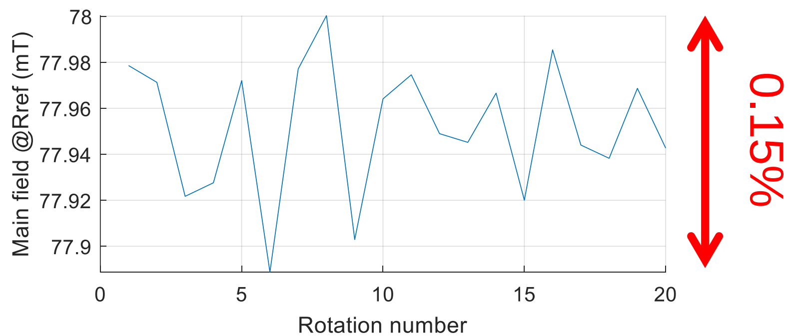


Absolute multipoles



Standard deviations





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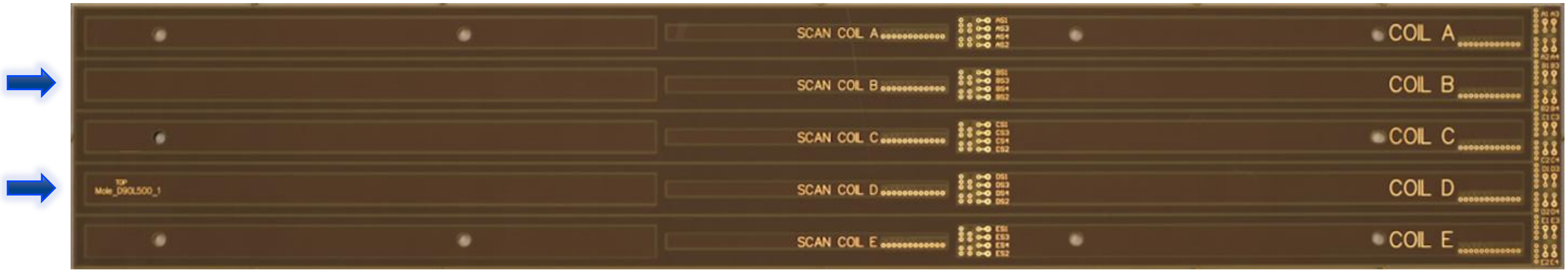
Proposed solution

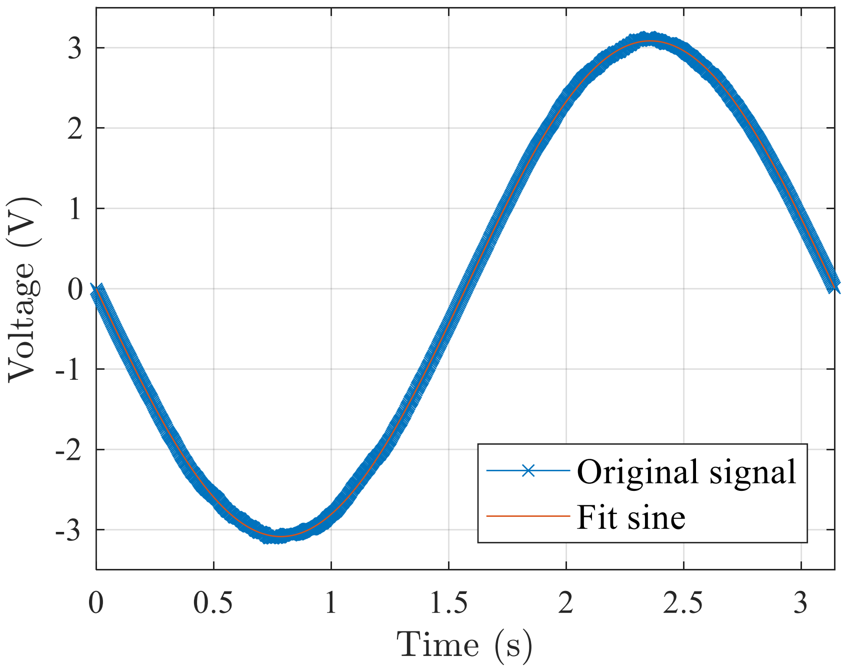
- In great majority of cases, accelerator magnets have a good quality field with **one main component**.
- We can use the relatively well know field of the magnet to **estimate the speed.**
- Sensitivity to higher order harmonics can be reduced by using coils with smaller rotation radius*
(e.g. the two marked coils - 2 and 4 out of 5 - are used in the following).

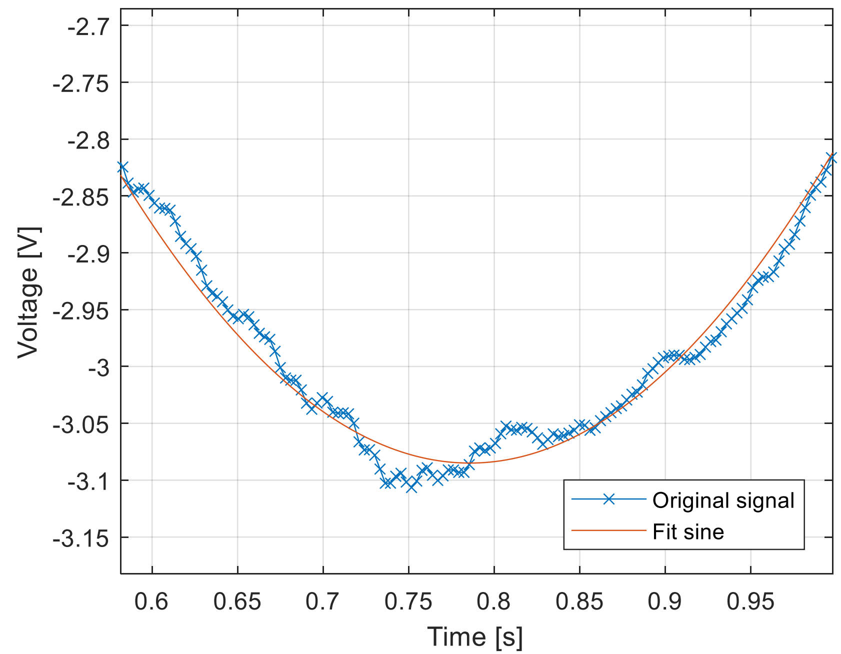


* This is due to the radial decay of the harmonics, that is increasing with their order – thus the intermediate coils will have half sensitivity to quadrupole, but for example for dodecapole (12-poles) the sensitivity is already 1/32 of the outer coils one.

Speed reconstruction

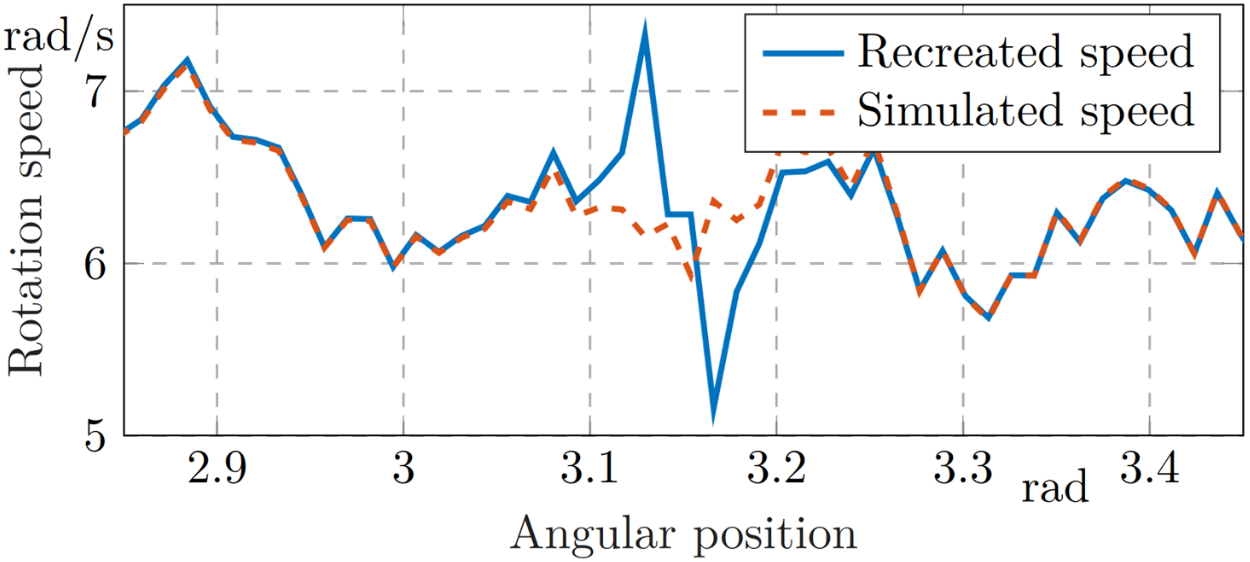
- In the simplest concept we can use an iterative approach to estimate the rotation speed at each step, which would ‘correct’ the deviation from a perfect sine.
- Using multiple turns helps to reduce the error of the amplitude and angular speed estimation for the expected best-fit sine.
- The problem is clearly ill-conditioned at zero-crossings of the induced voltage (or at the flux peaks, in case of using the integrated signals).





Speed reconstruction

- Simulated reconstruction results:
  - Even with negligible noise and numerical precision, the reconstruction diverges at voltage zero-crossings.
  - However, only small parts of the signal are affected.
  - A regularization is used to limit the extent of the problem – here, a simple threshold is used, where if the reconstructed speed deviates too much from the behavior in well-defined portions of the signal, it is substituted by an average.



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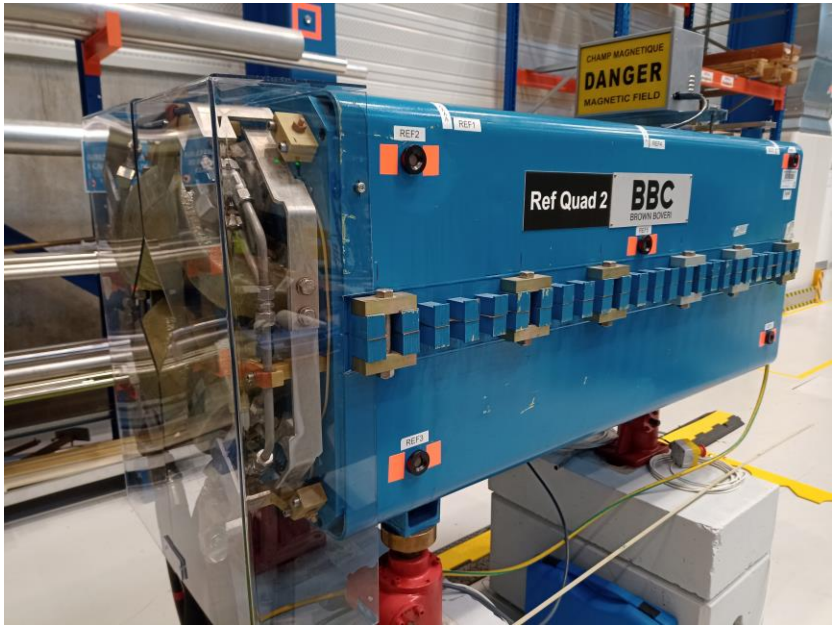
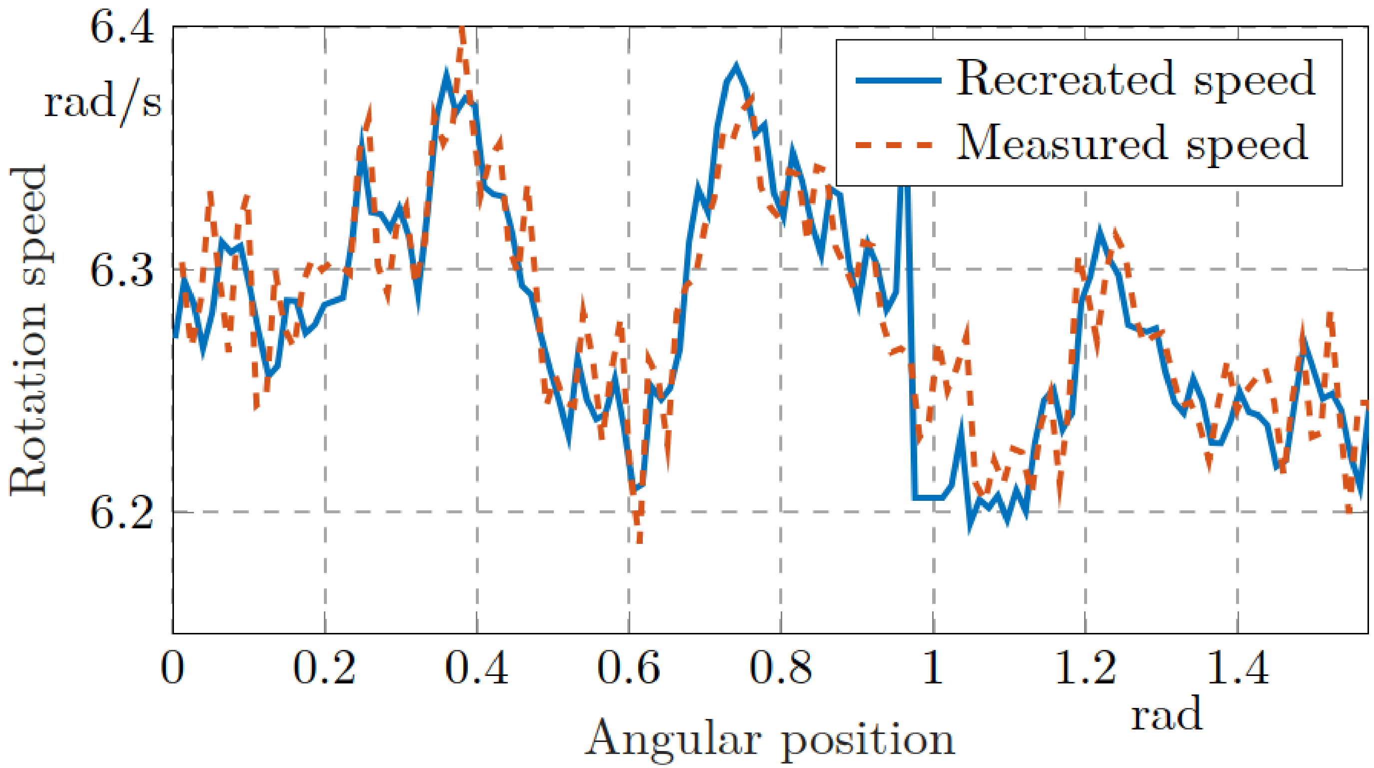
Test setup

- Rotating Coil Scanner in a reference quadrupole
- Acquisition both with integrators and an NI 6289 DAQ (integrators are encoder triggered for reference)
- Using external amplifier with filters
- Acquisition with smooth speed and speed variation of ~25%.



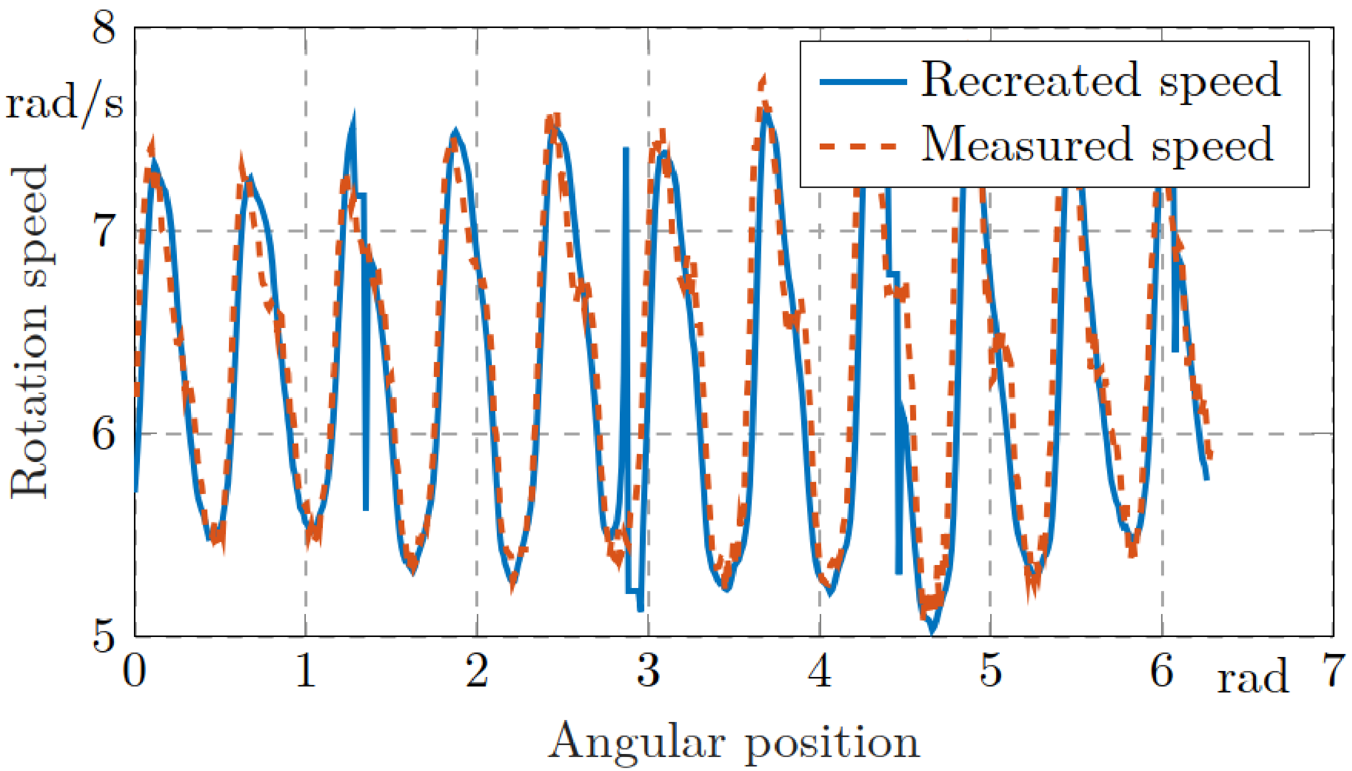
Speed reconstruction

- Low (~3%) speed variation



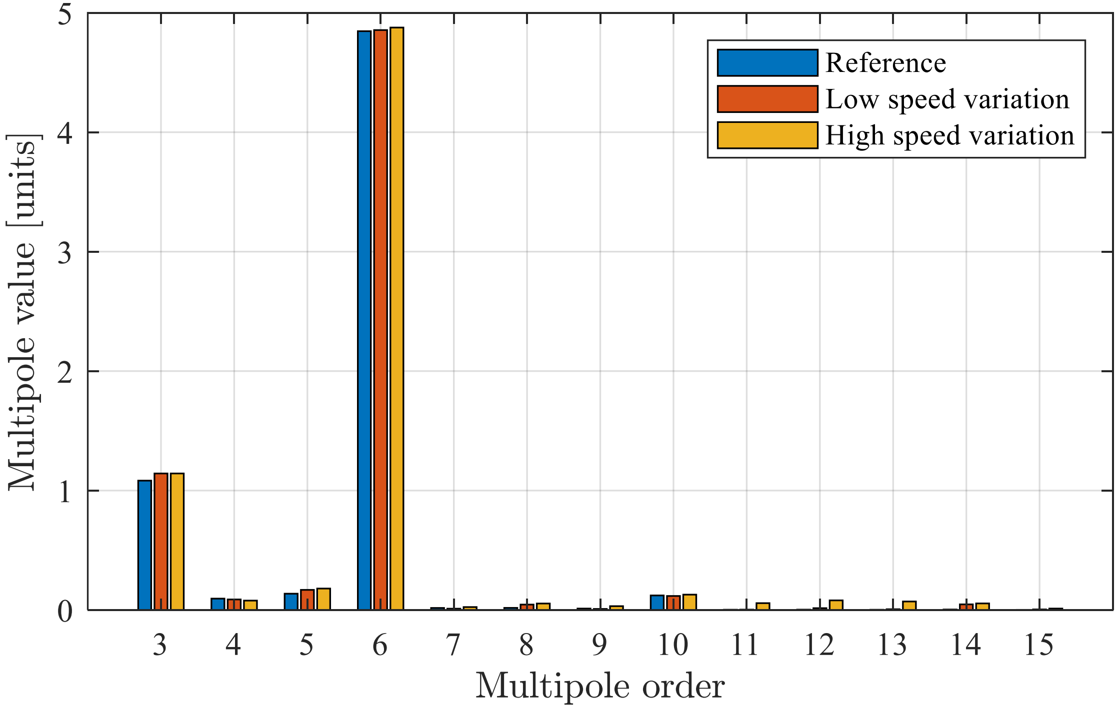
Speed reconstruction

- High (~25%) speed variation



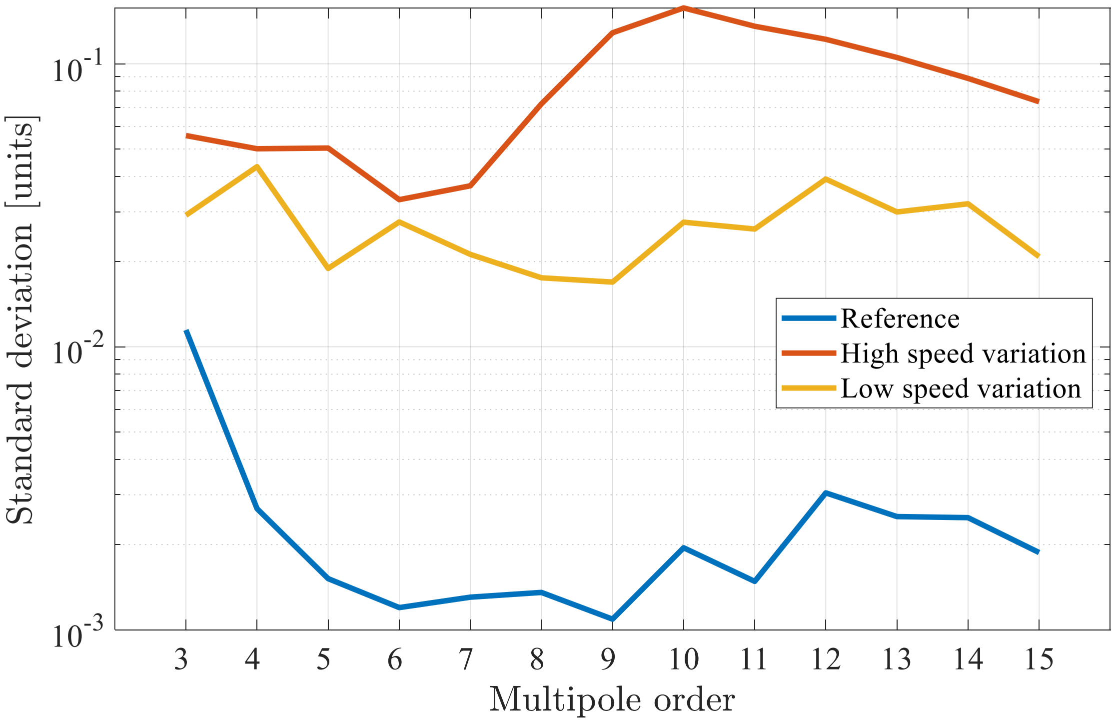
Results

- Multipole values (c_n magnitude)
  - reference radius of 42 mm,
  - normalized to the main field,
  - represented in units of 10^{-4},
  - measurements with encoder-triggered integrator used as reference.



Results

- Multipole variation (c_n relative magnitude)
  - reference radius of 42 mm,
  - computed over 20 rotations,
  - represented in units of 10^{-4},
  - measurements with encoder-triggered integrator used as reference.



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Advantages and Limitations

- ✓ No encoder – simpler and less expensive system design.
- ✓ Speed estimation exactly where the coils are – no need for extremely stiff transmission.

- – Field orientation measurements impossible without additional hardware.
- – Reconstruction is ill-conditioned at zero-crossings (upside – the effects of speed variation are smaller there too).
- – Good compensation necessary for good results (with current approach).

Next steps

- Additional, phase-shifted coils to address the ill-conditioning of the reconstruction.
- Addition of dedicated coils, even more selective to the main component.
- Better and more optimized reconstruction.
- Alternative indexing or angle resolving approach, shifting complexity from hardware to software.

Additional slides

No integration?

Challenges:

- Position measured by encoder:

No instantaneous speed measurement!

- No integration → no averaging of noise:

Single point measurement quality matters even more!

Effect on harmonics

- Voltage induced in a rotating radial coil:

$$U(\varphi) = \omega(\varphi) \sum_{n=1}^{\infty} n S_n^{\mathrm{rad}} \left[B_n \sin n\varphi + A_n \cos n\varphi \right]$$

- First, we assume the speed is known:

$$W(\varphi) = \frac{U(\varphi)}{\omega(\varphi)} = \sum_{n=1}^{\infty} n S_n^{\mathrm{rad}} \left[B_n \sin n\varphi + A_n \cos n\varphi \right]$$

Effect on harmonics

- Complex form:

$$W(\varphi) = \sum_{n=1}^{\infty} n S_n^{\mathrm{rad}} \left[B_n \sin n\varphi + A_n \cos n\varphi \right] = \sum_{n=-\infty}^{\infty} \underline{D}_n e^{\mathrm{i} n\varphi}$$

- Where:

$$\underline{D}_n = \frac{1}{2} \left(n S_n^{\mathrm{rad}} \left[A_n - \mathrm{i} B_n \right] \right) = \frac{1}{2\pi} \int_{-\pi}^{\pi} W(\varphi)\, e^{-\mathrm{i} n\varphi}$$

Effect on harmonics

- ... But speed is known only as an average between two triggers, so:

$$\underline{D}_n = \frac{1}{2\pi}\int_{-\pi}^{\pi}\frac{U(\varphi)}{\omega(\varphi)}e^{-\mathrm{i}n\varphi}\,\mathrm{d}\varphi$$

- becomes:

$$\underline{D}_n^a = \frac{1}{2\pi}\int_{-\pi}^{\pi}\frac{U(\varphi)}{\frac{1}{2\Delta\varphi}\int_{\varphi-\Delta\varphi}^{\varphi+\Delta\varphi}\omega(\varphi_0)\,\mathrm{d}\varphi_0}e^{-\mathrm{i}n\varphi}\,\mathrm{d}\varphi$$

Effect on harmonics

- Modelling variable speed as fourier series:

$$\omega(\varphi) = \omega_0 + \sum_{\substack{q=-\infty \\ q\neq 0}}^{\infty} \underline{\omega}_q e^{\mathrm{i}q\varphi}$$

- Yields:

$$\underline{D}_n^a = \frac{1}{2\pi}\int_{-\pi}^{\pi}\sum_{m=-\infty}^{\infty}\underline{D}_m e^{\mathrm{i}m\varphi}\frac{\omega_0 + \sum_q \underline{\omega}_q e^{\mathrm{i}q\varphi}}{\frac{1}{2\Delta\varphi}\int_{\varphi-\Delta\varphi}^{\varphi+\Delta\varphi}\underline{\omega}_q + \sum_q \underline{\omega}_q e^{\mathrm{i}q\varphi_0}\,\mathrm{d}\varphi_0} e^{-\mathrm{i}n\varphi}\,\mathrm{d}\varphi$$

Effect on harmonics

- Full expression for the effect on harmonics:

$$\underline{D}_n^a = \sum_m \underline{D}_m \frac{1}{2\pi}\int_{-\pi}^{\pi} e^{\mathrm{i}(m-n)\varphi} \frac{1+\sum_q \frac{\underline{\omega}_q}{\omega_0} e^{\mathrm{i}q\varphi}}{1+\sum_q \frac{\underline{\omega}_q}{\omega_0} e^{\mathrm{i}q\varphi} \frac{\sin q\Delta\varphi}{q\Delta\varphi}} \mathrm{d}\varphi$$

- Assuming speed variation to be relatively small yields:

$$\underline{D}_n^a = \underline{D}_n + \sum_m \underline{D}_m \frac{\underline{\omega}_{m-n}}{\omega_0}\left(1 - \frac{\sin(m-n)\Delta\varphi}{(m-n)\Delta\varphi}\right)$$

Effect on harmonics

- Matrix formulation:

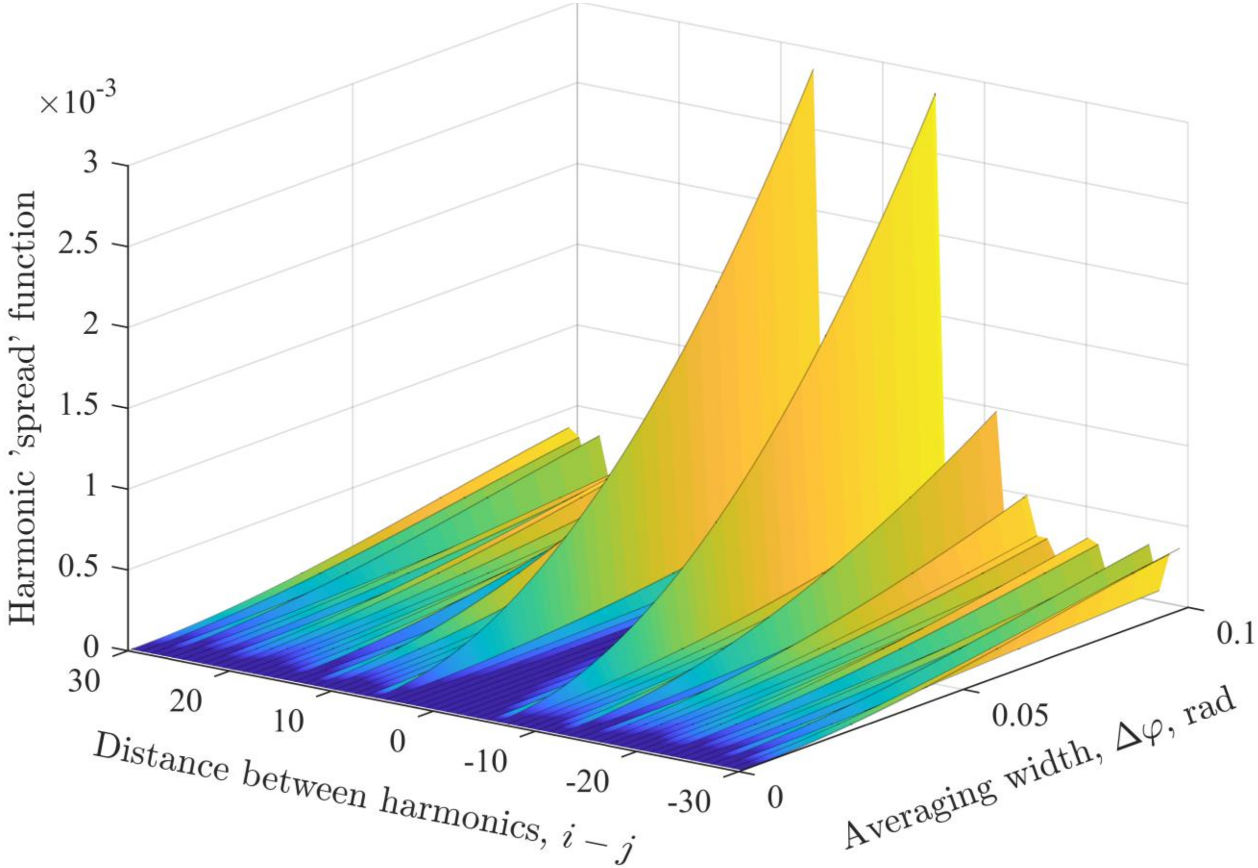
$$\overrightarrow{d}^{\,a} = \mathbf{M}\,\overrightarrow{d}$$

- Where:

$$m_{ij} = \begin{cases} 1\,, & \text{if } i = j \\ \frac{\omega_{j-i}}{\omega_0}\left(1 - \frac{\sin(j-i)\Delta\varphi}{(j-i)\Delta\varphi}\right)\,, & \text{otherwise} \end{cases}$$

”Distortion” function

$$\frac{\omega_{j-i}}{\omega_0}\left(1-\frac{\sin(j-i)\Delta\varphi}{(j-i)\Delta\varphi}\right)$$



Integrationless acquisition

With:

- **18-bit DAQ**, no simultaneous acquisition,
- **4096 steps** encoder and DC motor,
- **Amplifier + filter**, and **PCB coils**