Case study

MAGCAM
advanced
magnet
inspection

Maximizing Permanent Magnet Motor Efficiency with Magcam Technology

FISCHER Elektromotoren

FORMULA ELECTRIC BELGIUM

Insights from the Formula Electric Belgium 2023 Season

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By strategically selecting high-quality magnets, manufacturers can improve motor attributes like cogging torque and torque ripple by a factor of 2x to 4x.

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Introduction

Magnet quality matters for the performance of permanent magnet electric motors. That is the main conclusion of this case study, where we show that e-motor manufacturers can realize an impressive factor of 2x to 4x improvement on key motor performance characteristics, such as torque ripple and cogging torque, by optimizing magnet quality in the early stages of motor production.

These results open up new possibilities for high-end electric motor/generator applications. In the automotive sector these include motor sports and high performance consumer cars, as well as the broader electric mobility market. The results equally apply to other application fields of electric motors, such as aviation, industrial automation, consumer goods and medical equipment. Keep reading to find out how Magcam can help you unlock the untapped potential of your permanent magnet electric motors.

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“This season, we experienced a significant decrease in issues related to the current control of the motors. This improvement can be attributed in large part to a reduction in torque/current ripple, a development made possible through the meticulous optimization of the rotors by Magcam.”

FORMULA ELECTRIC BELGIUM

Background

When the Formula Electric Belgium team sought to optimize the performance of their 2023 season race car, they partnered with Magcam, expert in magnet inspection, and Fischer Elektromotoren GmbH, a top-tier German electric motor manufacturer, to ensure magnetic quality in their four radial-flux permanent magnet synchronous electric motors, one for each wheel.

The 2023 Formula Electric Belgium team with their full electric race car 'Apollo', containing the four radial-flux permanent magnet motors optimized by Magcam. Source: www.facebook.com/formulaelectricbelgium/posts/730519009084633

While Fischer supplied the magnets and took charge of rotor and motor assembly, Magcam's expertise centered on ensuring the magnetic quality of these electric motor rotors. This was accomplished using Magcam's unique magnetic field camera measurement technology, combined with its advanced data analysis capabilities, applied to both the individual magnets, before assembly, and to the assembled rotors.

The objective was not only to enhance the performance of the vehicle but also to provide a comparative analysis by creating a 'worst-case' rotor made from deliberately chosen poor quality magnets. Keep on reading to find out how Magcam achieved this and what can be learned from the results.

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Batches of magnets typically contain large variations in quality parameters, which results in sub-optimal end products.

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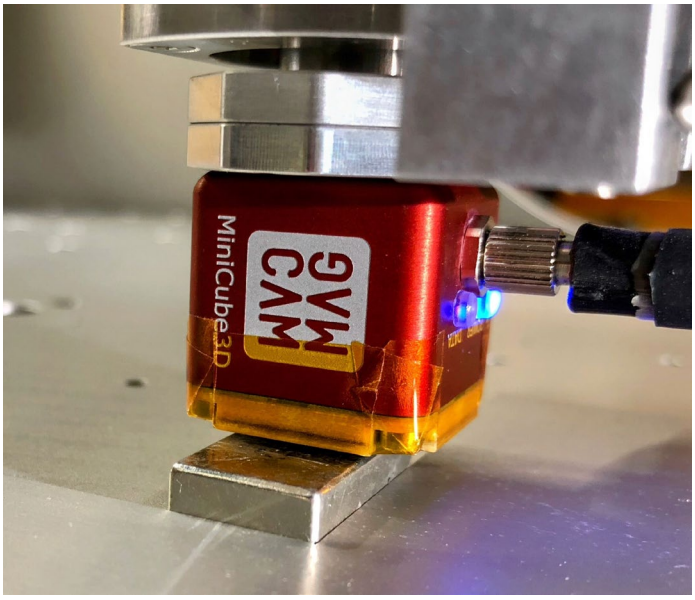
Magnetic Field Measurements and Selection of the Magnets

Individual Magnet Scans by Magcam

The study started with Magcam employing its sophisticated magnetic field camera Combi Scanner to measure high resolution magnetic field distributions of 200 magnets provided by Fischer. The batch size was far larger than the number of magnets needed for the rotors, since it was anticipated that a substantial portion of the magnets would have to be rejected based on their quality.



Magcam's MiniCube3D magnetic field camera

The measurements involved stepping Magcam's MiniCube3D magnetic field camera over the magnet surface in a few steps at high speed and subsequently stitching the individual frames together. The integrated on-chip 2D array of over 16000 Hall effect sensors allowed for short cycle times, limiting the full batch measurement time to a few hours.

From the subsequent analysis of the measured magnetic field distribution data emerged an array of quality parameters for each magnet, including magnet strength, magnetization angle error, and localized magnetic homogeneity maps, allowing in-depth quality assessments, unparalleled by any other magnetic inspection technique.

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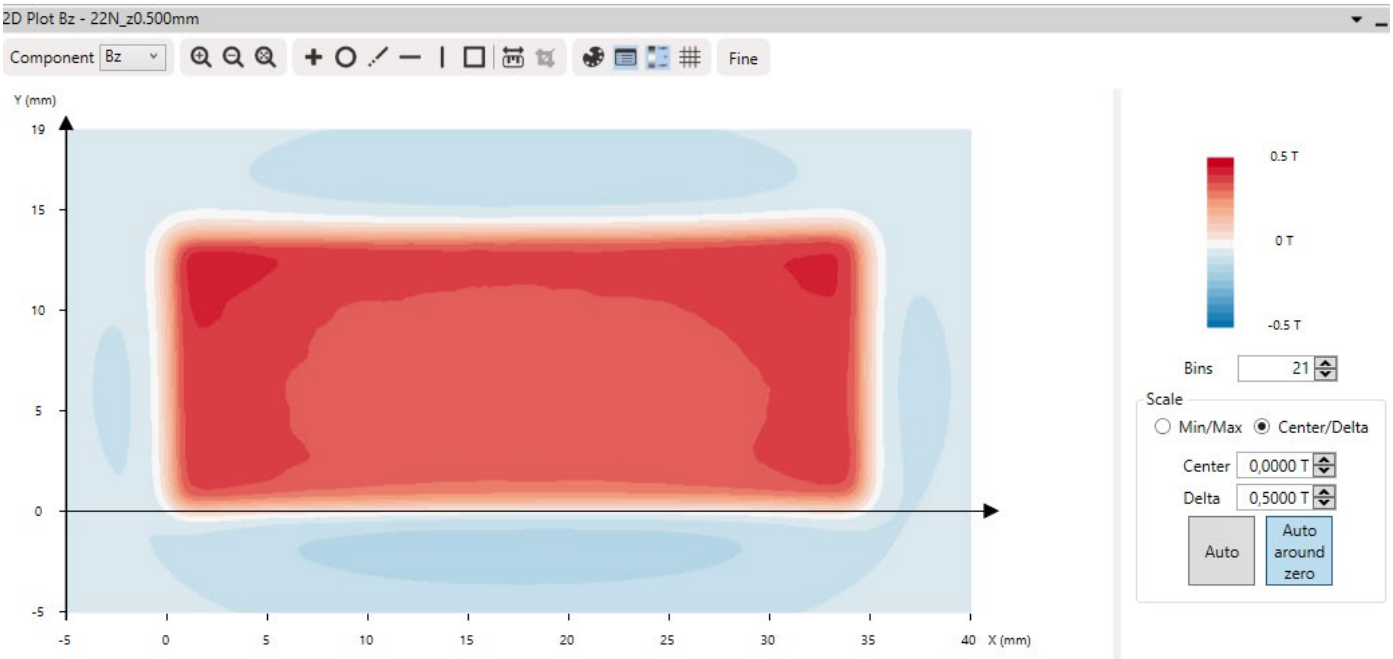
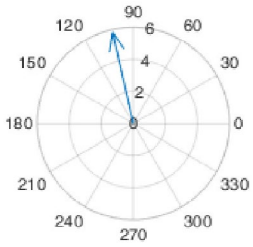
After pouring these results in histograms, the quality variation within the batch of magnets could be visualized and further analyzed. The objective? To identify the most optimal magnets from the batch for the race car rotors, while also selecting a set of inferior quality magnets for a 'worst-case' rotor, in order to show the potential consequences of poor magnet quality.



	Result	Unit
M-direction	3	-
M	1.3978	T
theta	5.8362	°
phi	102.7913	°

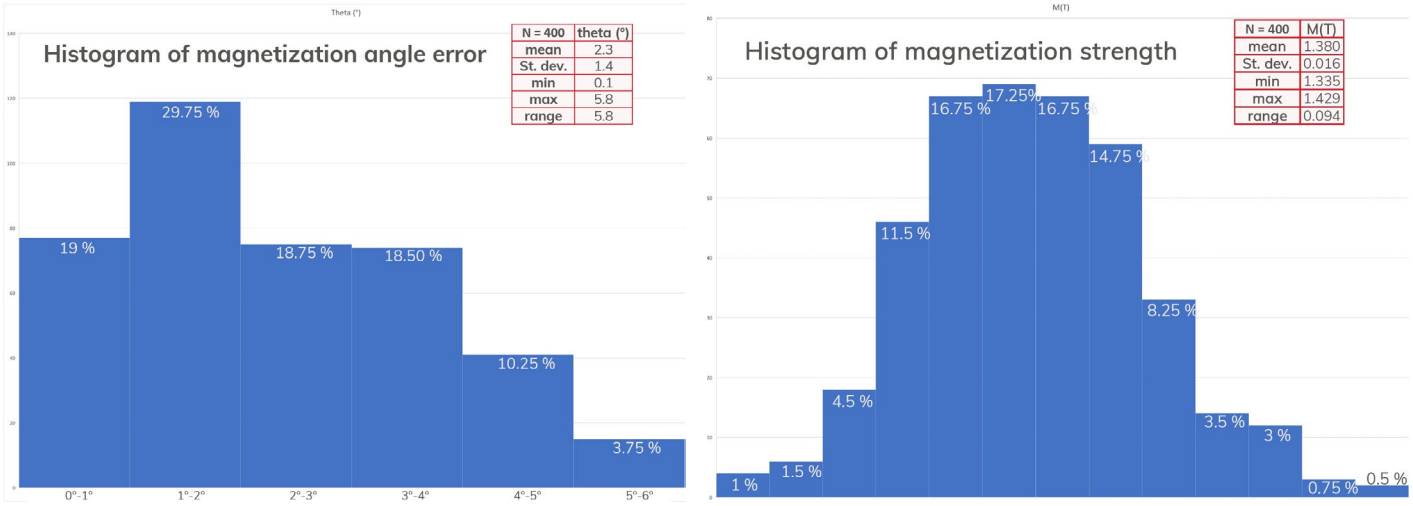


Magcam measurement and analysis of the magnetic field distribution of a single rotor magnet. ©Magcam NV

A first pre-selection was done by rejecting all magnets that exhibited a too large magnetization vector angle deviation, leaving only about half the magnets in the running. Next, magnets that exhibited large inhomogeneities within their internal magnetization distribution were also removed, a characteristic that can only be measured using the combination of magnetic field mapping and Magcam's

proprietary analysis algorithms. Within this remaining set of magnets, there still existed a considerable variation in internal magnetization strength, a metric that Magcam's algorithms can also extract from the external magnetic field distribution. Since the goal was to create high-performing motors, high-strength magnets with tight tolerances were selected, while at the same time maximizing the homogeneity of magnet quality among the four rotors. This careful selection resulted in 4 sets of high-caliber magnets, one for each rotor.

Another set of lesser-quality magnets was picked for the 'worst-case' rotor, exhibiting a large variation in magnet strengths, angle deviations and magnet inhomogeneities, in order to see how such motor would perform on functional motor tests.



Resulting batch histograms of magnetization angle deviation (left) and magnetization strength (right), showing the considerable variation in a typical magnet batch. ©Magcam NV

Findings

- **Variances in magnet quality were evident, even from recognized suppliers. This underscored the significance of a meticulous pre-assembly evaluation.**
- **By cherry-picking the best magnets, Magcam allowed Fischer to assemble high-performance rotors.**

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High-speed, high-resolution Magcam measurements allow to screen magnets on an array of quality metrics and prevent bad magnets from getting into a finished product.

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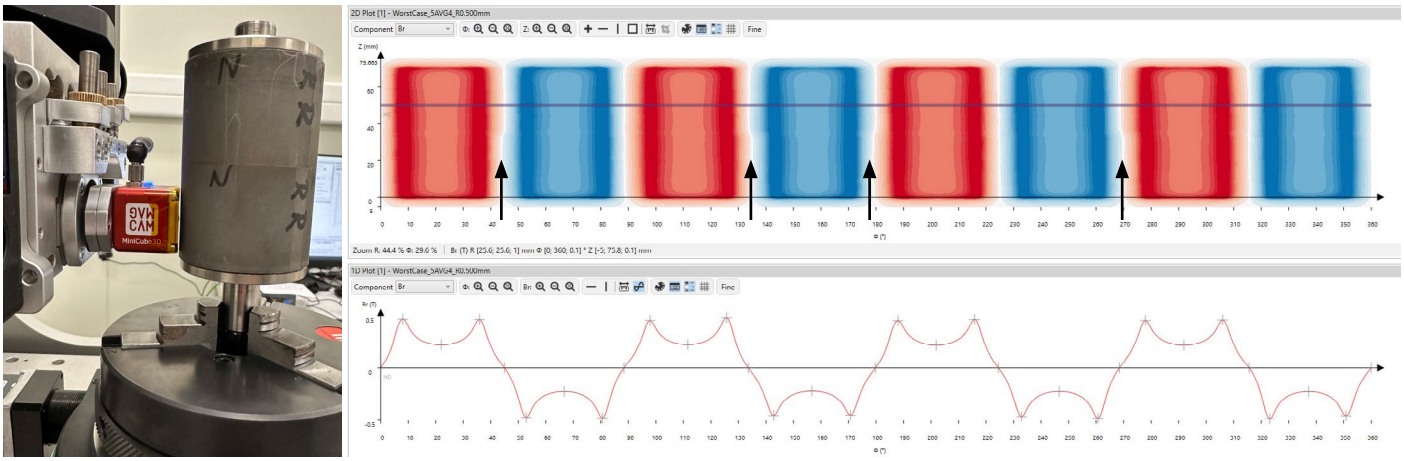
Assembling, Measuring, and Analyzing the Rotors

Rotor Assembly by Fischer Elektromotoren

Once the magnets were meticulously selected, it was Fischer's turn to assemble the four optimized rotors, as well as the 'worst-case' unit. All rotors were assembled following the exact same expert procedure, so any differences between the rotors would be mainly due to the quality of the magnets inside, with some additional influence of tolerances in the assembly process.

Rotor Magnetic Field Scans & Analysis by Magcam

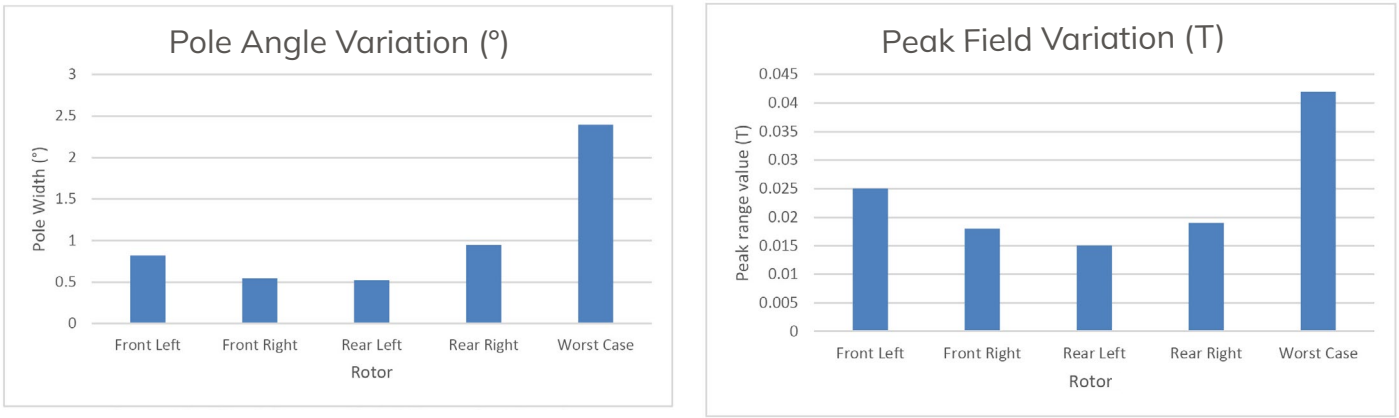
Following assembly, Magcam's Combi Scanner was once again in action to measure fast, high resolution magnetic field distribution maps of the rotors. Before the measurements, an initial automatic runout correction on the rotor shafts was performed to ensure a runout-free measurement. The resulting magnetic field maps were analyzed using Magcam's sophisticated algorithms in order to unveil magnetic rotor parameters including pole angle consistency, pole strength uniformity, field gradient variations and and north/south symmetry, with the aim to later on correlate these metrics with functional motor tests.



Magcam rotor measurement and resulting magnetic field distribution (worst-case rotor). Pole angle variations due to magnet quality fluctuations are already visible by the naked eye (indicated by black arrows). ©Magcam NV

Comparing the resulting magnetic rotor metrics among the five constructed rotors immediately pointed to a crystal clear observation: the ‘worst-case’ rotor, consisting of magnets with a large variation in quality parameters, showed between 2 and 4 times as large variations in the key magnetic rotor quality metrics compared to the optimized rotors, where the magnets were selected according to narrow tolerances.

Apart from this astounding difference, smaller differences were observed among the four optimized rotors. Since for all these rotors the magnets were meticulously selected with tight tolerances on their quality parameters, these remaining differences are believed to be due to tolerances in the rotor assembly process. This indicates that further improvements in rotor quality, and therefore motor performance, can be achieved by optimizing the rotor assembly process, which can be verified by Magcam rotor measurements.



Summary graph of pole angle (left) and peak field (right) variations for all rotors. The ‘worst-case’ rotor sticks out by a factor of 2x to 4x. The field gradient variations (not shown) display a similar pattern. ©Magcam NV

Insights

- **The optimized rotors, assembled using the best-selected magnets, demonstrate between 2x and 4x better performance on key magnetic metrics in comparison to the 'worst-case' rotor.**

- **Smaller differences among the optimized rotors are still observed, deemed to be due to assembly tolerances, showing the potential to further perfect the assembly process.**

- **This comprehensive analysis demonstrates the direct benefits of a two-stage quality control: first, in magnet selection, and second, after rotor assembly.**

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A rotor consisting of magnets with a large variation in quality parameters can show between 2x and 4x as large variations in key magnetic rotor quality metrics compared to a rotor where the magnets were pre-selected according to narrow tolerances.

These magnetic quality metrics can be measured using Magcam equipment, both on the individual magnets and on the assembled rotors.

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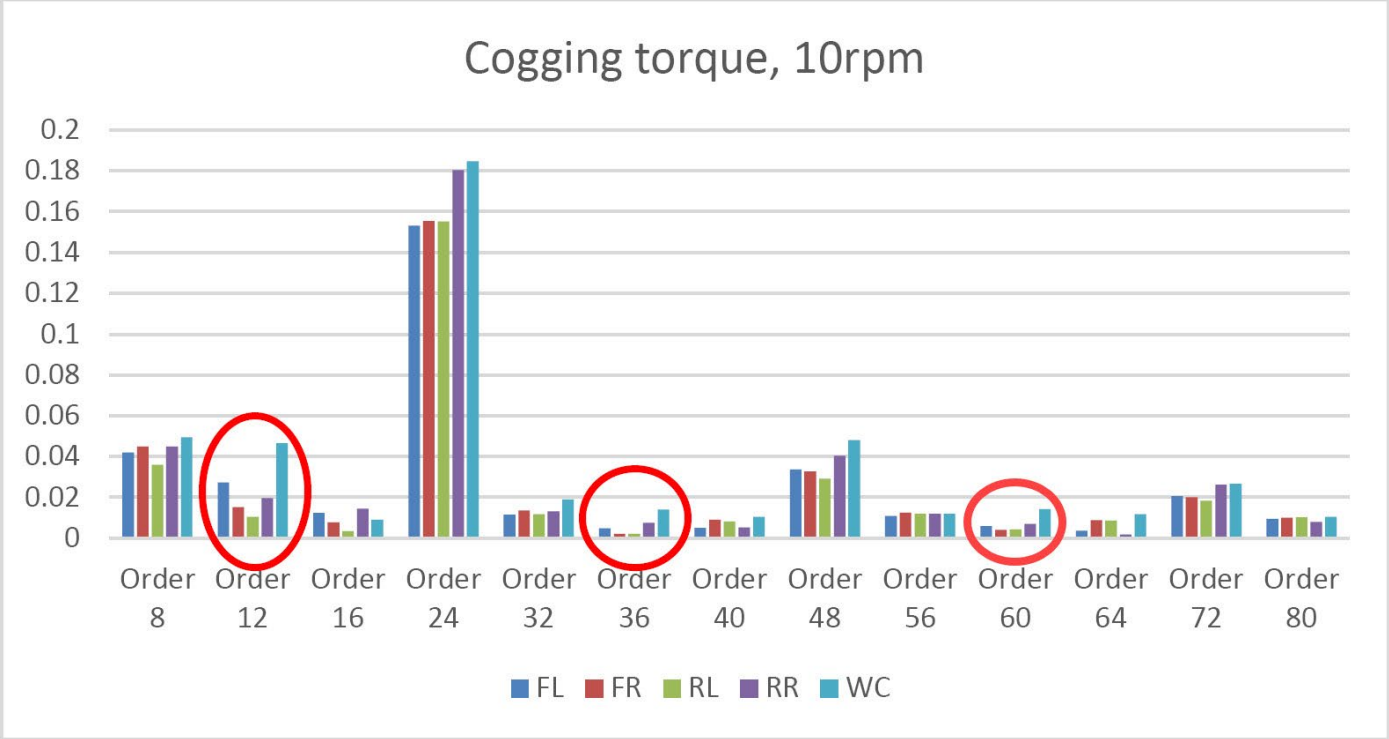
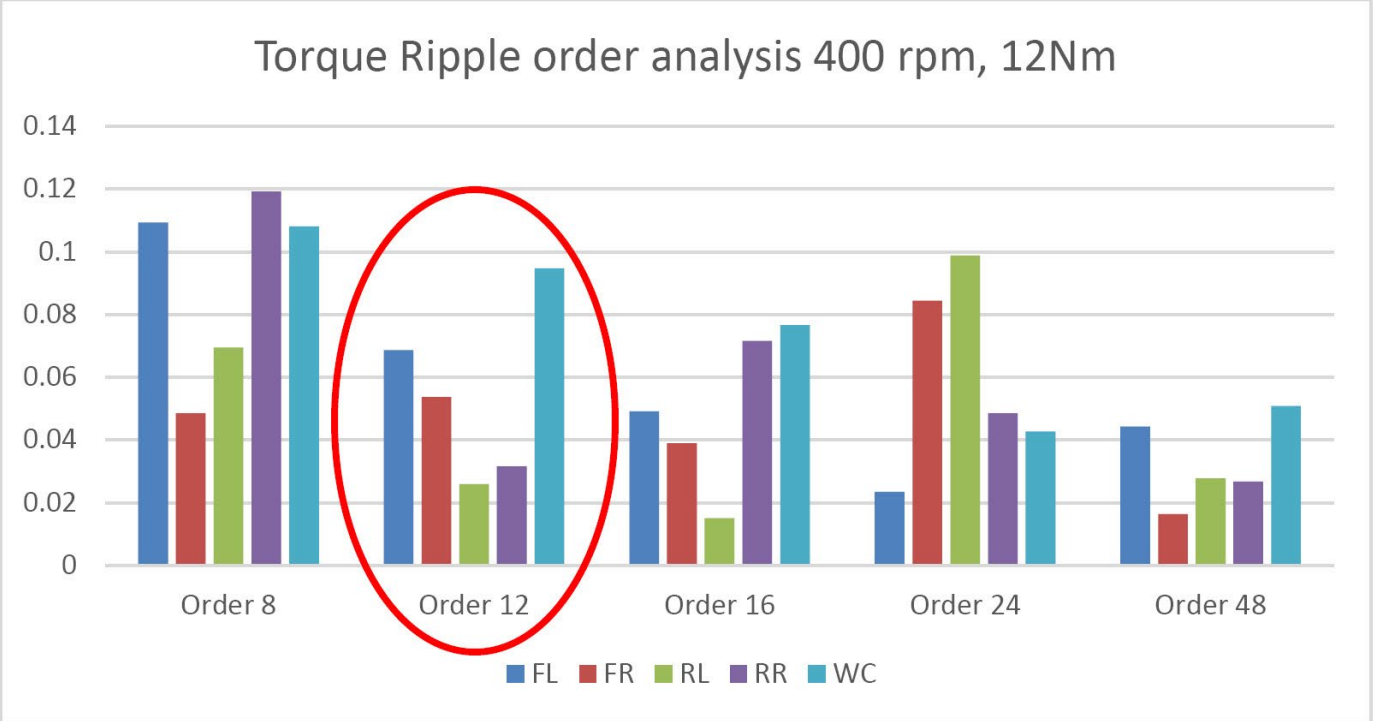
Functional Motor Tests and Correlation Analysis

Motor Tests by Formula Electric Belgium Team

Armed with the assembled rotors, the Formula Electric Belgium team performed functional tests on the finished motors, focusing on key performance metrics such as torque ripple and cogging torque, which are essential parameters in electric motors used in automotive applications. Their tests resulted in a Fourier analysis of the torque ripple and cogging torque of all five produced motors.





Cogging torque (top) and Torque ripple (bottom) measurement results on finished motors. Note the relative values of the different motors in the rotor-relevant harmonics (red circles). ©Formula Electric Belgium

Comparative Analysis & Correlation by Magcam

When looking at the resulting graphs of the rotor-relevant harmonics of the cogging torque and torque ripple of the motors, a familiar picture was observed: the values of the optimized rotors were found to be a factor of 2x to 4x better than those of the worst-case rotor. Moreover, the relative values of these functional metrics perfectly mirrored those of the various magnetic quality parameters obtained from the Magcam rotor measurements.

The powerful conclusion of this comparative analysis: the magnetic quality parameters obtained from Magcam measurements on the rotors correlate perfectly with cogging torque and torque ripple in the final motors! In other words: final motor performance can be predicted from the measured magnetic pole angle deviations, magnetic peak field variations and field gradient variations from a Magcam rotor measurement, without the need for assembling a full motor.

This conclusion opens the door to tremendous cost savings, as bad rotors can be scrapped before motor assembly, thereby saving time and material, by performing a magnetic scan of the bare rotor.

Conclusions

- **A clear and direct correlation emerged between motor performance, rotor magnetic field distribution metrics and the quality of magnets utilized.**

- **Motor manufacturers can optimize motor performance by a factor of 2x up to 4x through individual magnet quality control before rotor assembly.**

- **Motor characteristics can be predicted from the measured magnetic field distribution of the assembled rotor, before final motor assembly.**

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The improvements seen in Magcam rotor measurements, ranging from 2x to 4x, are mirrored in the final motor performance. This provides motor manufacturers with a valuable tool for both optimizing and validating motor quality.

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Key Take-Aways for the Electric Motor Industry

1. Even within a single magnet batch, there can be a vast range of variation. To fabricate top-tier rotors, these variations need to be reduced. Supplier magnet quality screening, pre-assembly measurement and magnet pre-selection lead to significantly better final products.

2. Using the Magcam magnetic field camera scanner and MagScope data analysis software, motor engineers can optimize key magnetic rotor parameters, such as pole width variations and field uniformity, leading to 2x to 4x improvements compared to rotors assembled with inferior magnets.

3. By strategically selecting high-quality magnets, manufacturers can improve motor attributes like cogging torque and torque ripple by a factor of 2x to 4x.

4. By measuring the magnetic field distribution of assembled rotors (even without pre-selected magnets), magnetic rotor parameters can be gauged to assess rotor quality and even predict functional motor characteristics before full motor assembly, thereby saving time and scrap.

5. Magcam can assist motor manufacturers and magnet suppliers at every stage of motor development and production by providing top notch magnet inspection equipment, along with expert advise and service.

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About the partners

Magcam NV

MAGCAM advanced magnet inspection

Magcam is the technology leader in permanent magnet inspection based on its unique magnetic field camera technology. Magcam's hardware, software, and services work closely together to measure, visualize, and analyze full three-dimensional magnetic field distributions with high spatial resolution at high speed for in-depth analysis of permanent magnets, permanent magnet rotors, and other magnet assemblies. Magcam's complete solution guarantees a better development of high-end applications of permanent magnets, improved incoming and outgoing quality control, and 100% in-line production testing. Magcam's expert team also offers measurement and analysis services, application consulting services and of course outstanding customer support.

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Fischer Elektromotoren GmbH

Fischer are experts in the development and production of high quality, customer-specific electric motors of different types, offering comprehensive services, from development and design to reliable series production. Their services also includes the professional repair of electric motors, gear motors, servo motors, pumps, fans, electrical appliances and other drive systems.

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Formula Electric Belgium

Formula Electric Belgium unites a group of motivated engineering students from different campuses of KU Leuven University and Thomas More University College in Belgium. Each season a new electric race car is designed, built and driven at several events in the international Formula Student competition. The team is supported by partners who help realize the building of the car. For the 2023 season, Magcam and Fischer are supporting them with the optimization of their electric motors.

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Start improving your electric motor performance

As demonstrated in this case study, achieving remarkable enhancements in electric motor performance is within reach when equipped with the right tools and partnered with the right expertise. Magcam stands as your trusted ally, offering state-of-the-art technology to facilitate unprecedented advancements in motor performance. Don't settle for less; reach out to us today to explore how we can support you to craft top-tier electric motors that set new industry standards.

Contact Magcam's Experts

Are you ready to optimize the performance of your electric motors? Contact us today to discuss your application, so we can help you make top-quality electric motors.

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