RIGA TECHNICAL UNIVERSITY
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DESIGN OPTIMIZATION OF CYLINDRICAL MAGNETIC COUPLER BASED ON CALCULATIONS OF MAGNETIC FIELD

Summary of Doctoral Thesis

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DOCTORAL THESIS
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To be granted the degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council "RTU P-14" on 13 May 2015, at the Faculty of Power and Electrical Engineering, Riga Technical University, Azenes Str. 12/1, Room 212.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the degree of Doctor of Engineering Sciences, is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to any other scientific degree.

Baiba Ose-Zaļā …………………………….
(Signature)

Date: 12 February 2015

The Doctoral Thesis has been written in English. It contains introduction, 5 chapters, main conclusions, 8 appendices and bibliography with 190 reference sources. It has been illustrated by 72 figures and 15 tables. The volume of the present Doctoral Thesis is 139 pages.

CONTENTS

GENERAL DESCRIPTION OF THE RESEARCH

Topicality

The cylindrical magnetic couplers (CMCs) are used in many different production and research areas such as physics, biology, chemistry, pharmacy, food processing industry, gas and oil industry etc. [15, 16]. In these areas the handling and transfer of substances (liquids, gases and solid particles) occur in the aggressive or sterile environment; the CMC, in turn, ensures the necessity of hermetic conditions as the magnetic-mechanical energy or torque transmission is contactless [19].

Though the CMCs are widely used, only in the last two decades the enterprises dealing with coupler manufacturing have started using the high-energy permanent magnets (PMs) made of rare-earth alloys such as neodymium-iron-boron (NdFeB) and samarium-cobalt (SmCo). However, in electrical machine production the use of these rare-earth alloy PMs began in the 1980s. Initially, PMs made of aluminium-nickel-cobalt alloys and ferrites like barium-ferrite (BaFe) or strontium-ferrite (SrFe) were used in magnetic couplers [1, 17, 20]. Thus, it is important to consider which permanent magnet material should be used in a CMC nowadays.

Most of the CMC manufacturers provide the couplers with rectangular PMs; the transition to rounded PMs should be considered.

Many CMC manufacturers offer the couplers from ready-made products, which (as the manufacturers admit it in interviews) were optimized a relatively long time ago. Thus, the optimization of CMC design is necessary to be made as well as the optimization methodology for CMCs.

Most often the real prototypes of CMC are made to study the coupler characteristics, but it is an expensive and ineffective option taking into account the waste of time and material consumption. Thus, the new (not yet existing) mathematical models should be created.

Subject and Object of the Research

The cylindrical magnetic coupler is the **object** of the research. Both types (active and reactive) CMCs are studied. CMC design parameters are the **subject** of the research. Together six parameters — five design parameters and one PM material characterizing parameter that also influences the dimensions of design — are chosen to be studied.

Aim and Tasks of the Research

The aim of the research is to develop the methodology for obtaining the most optimal combination of cylindrical magnetic coupler design parameters according to the chosen boundary values of variables and so that the CMC has the highest effectiveness. By its effectiveness we understand the best value of ratio: maximum mechanical torque per volume.

Consequently, the tasks are as follows:

1. To overview the latest studies about CMC design and its optimization;
2. To choose the main CMC characteristic and its influencing design parameters;
3. To choose the base design of CMC, for which the optimization will be made, and the boundary values of independent variables;
4. To develop the calculation methodology and to choose the application software for obtaining the basic characteristics;
5. To define the objective function, to synthesize the necessary mathematical models/ formulas that will be used in optimization;
6. To analyze the optimization algorithms, to choose the optimization tool, to obtain the most optimal CMC design parameters, and to develop the optimization methodology for CMCs;
7. To make the CMC samples and to test them experimentally;
8. To compare experimental results with data obtained by the developed calculation methodology and the developed mathematical models.

Research Methods and Tools

The following research methods have been used within the present research:

- Qualitative:
  - ✓ Interviews;
  - ✓ Grounded theory.
- Quantitative:
  - ✓ For calculation methodology development — *AutoCad*, *QuickField* (based on finite element analysis/method) and *SIMCA* (multivariate data analysis and optimization tool);
  - ✓ Experiment planning;
  - ✓ For formula synthesis — program tool (based on regression models).

Scientific Novelty of the Research

The used methods and performed research have allowed achieving the following scientific novelties:

1. The chosen software tools (*AutoCad*, *QuickField*) have allowed developing the calculation methodology for obtaining CMC physical parameters (of interest such as mechanical torque, its maximum value, and magnetic flux density, its maximum values in the yokes) based on the calculations of coupler magnetic field (publications, e.g., [6–9]);
2. The proposed transition from rectangular permanent magnets to rounded ones increases the value of maximum mechanical torque by more than 30 % (publication [6]);
3. The transition from disc form MC to cylindrical MC in the water counters has allowed averting the external influence from strong permanent magnets on the counting system of consumed water (Latvian patent [10]);
4. The new design reactive MC has been developed that increases the value of maximum mechanical torque compared to the same dimension analogous reactive couplers (Latvian [12] and European [11] patents and publication [8]);
5. The new previously non-existent mathematical models/formulas of active CMC have been synthesized for certain boundaries of the chosen variables, thus enabling one to forecast the values of maximum mechanical torque, maximum mechanical torque per volume, and the maximum values of magnetic flux densities (publication [5]);
6. The optimization of CMC has been made (in the chosen *SIMCA* tool) by synthesized new models/formulas, which allowed developing the optimization methodology for CMC. The optimum design of CMC (with rounded permanent magnets) has been manufactured and tested; the experiments have proved the expected results.

Scientific and Practical Approbation of the Research

The research results and given scientific novelties are scientifically approbated in publications (see *Author's Publications*), conference reports, and Latvian and European patents (see *Inventions*), and practically approbated in the CMC manufacturing at the Latvian enterprise "Environment, Bioenergetics and Biotechnology Competence Centre" (also shortly named BTC) where the couplers are implemented in mixers, and these mixers are sent to Germany for use in the laboratory equipment.

The research results have been reported in the following international conferences:

1. "The influence of Pole Pair Number and Magnets' Width on Mechanical Torque of Magnetic Coupler with Rounded Permanent Magnets". *The 52nd International Conference of Riga Technical University*. Latvia, Riga, 14 October, 2011;
2. "The Influence of PM's Construction Parameters in Magnetic Coupler on Its Mechanical Torque". *The 6th International Conference on Electrical and Control Technologies* (*ECT 2011*). Lithuania, Kaunas, 4–6 May, 2011;
3. "The influence of permanent magnets' width and number on the mechanical torque of a magnetic coupler with rectangular permanent magnets". *IEEE International Symposium on Industrial Electronics* (*ISIE 2011*). Poland, Gdansk, 27–30 June, 2011;
4. "The Formula Synthesis of the Maximal Mechanical Torque on the Volume for a Cylindrical Magnetic Coupler". *The 53rd International Conference of Riga Technical University*. Latvia, Riga, 12 October, 2012;
5. "The Comparison of Active and Reactive Magnetic Couplers". *The 8th International Conference on Electric Power Quality and Supply Reliability* (*PQ 2012*). Estonia, Tartu,11–13 June, 2012;
6. "Magnetic Coupler instead of Lever Actuated Friction Clutch for Wind Plant". *Conference ELECTRONICS'2012*. Lithuania, Palanga, 18–20 June, 2012;
7. "Start-Up Torques of Permanent Magnet Synchronous Generator With Non-Overlapping Concentrated Windings*". The 9th International Conference on Electric Power Quality and Supply Reliability* (*PQ 2014*). Estonia, Rakvere, 11–13 June, 2014.

Inventions

For some of the research results the following patents have been received:

1. V. Pugacevs, **B. Ose-Zala**, J. Zicans, R. Merijs-Meri. Reactive magnetic coupler. EP2733835A2, 21.05.2013.
2. V. Pugačevs, **B. Ose-Zaļā**, J. Zicāns, R. Merijs-Meri. Reaktīvais magnētiskais sajūgs. LV 14857, 16.11.2012.
3. V. Pugačevs, J. Dirba, N. Levins, S. Orlova, **B. Ose**, L. Ribickis. Sinhronais ģenerators ar pastāvīgajiem magnētiem. LV 14271, 08.12.2010.
4. V. Pugačevs, A. Ivanovs, B. Tarancevs, **B. Ose**. Ūdens patēriņa skaitītājs. LV 14434, 17.08.2011.

Author's Publications

Research results (obtained in the present Doctoral Thesis) have been presented in the following publications (in brackets the database and DOI number are given — if any):

1. **Ose-Zala B**., Pugachov V., Levin, N. Start-Up Torques of Permanent Magnet Synchronous Generator With Non-Overlapping Concentrated Windings. *Proceedings of the 9th International Conference on Electric Power Quality and Supply Reliability* (*PQ 2014*). Estonia, Rakvere, 11–13 June, 2014. P.: 195–198. (**IEEE Xplore Digital Library, SCOPUS** doi: 10.1109/PQ.2014.6866809);
2. Dilevs G., **Ose-Zala B**., Jakobsons E. Self-excitation of Low-speed Inductor Generator. *Latvia Journal of Physics and Technical Sciences*. No. 4. Vol. 49. 2012. Latvia, Riga. P.: 21–28. (**SCOPUS** doi: 10.2478/v10047-012-0020-6);
3. Levins, N., Orlova, S., Pugachov, V., **Ose-Zala, B.**, Jakobsons, E. Methods to Reduce the Cogging Torque in Permanent Magnet Synchronous Machines. *Journal of Electronics and Electrical Engineering*. No. 1. Vol. 19. 2013. Lithuania, Palanga 18–20 June. P.: 23–26. (**SCOPUS** doi: 10.5755/j01.eee.19.1.3248);
4. **Ose-Zala B**., Jakobsons E., Suskis P. The use of Magnetic Coupler instead of Lever Actuated Friction Clutch for Wind Plant. *Journal of Electronics and Electrical Engineering*. No. 10. Vol. 18. 2012. Lithuania, Palanga 18–20 June. P.: 13–16. (**SCOPUS** doi: 10.5755/j01.eee.18.10.3053);
5. **Ose-Zala B**., Pugachov V. The Comparison of Active and Reactive Magnetic Couplers. *Proceedings of the 8th International Conference on Electric Power Quality and Supply Reliability* (*PQ 2012*). Estonia, Tartu, 11–13 June, 2012. P.: 25–28. (**IEEE Xplore Digital Library, SCOPUS** doi: 10.1109/PQ.2012.6256194);
6. **Ose-Zala B**., Pugachov V., Onzevs O. The Formula Synthesis of the Maximal Mechanical Torque on the Volume for a Cylindrical Magnetic Coupler. *Scientific Journal of Riga Technical University on Electrical, Control and Communication Engineering*. Is. 1. Vol. 3. August, 2013. P.: 37–43 (**Open Access** doi: 10.2478/ecce-2013-0013);
7. **Ose B**., Pugachov V. The Influence of Pole Pair Number and Magnets' Width on Mechanical Torque of Magnetic Coupler with Rounded Permanent Magnets. *Proceedings of the 52nd International Scientific Conference of Riga Technical University on Power and Electrical Engineering*. Latvia, Riga, 14 October 2011. P.: 63–66.

8. **Ose B**., Pugachov V., Orlova S., Vanags J. The Influence of Permanent Magnets' Width and Number on the Mechanical Torque of a Magnetic Coupler with Rectangular Permanent Magnets. *Proceedings of IEEE International Symposium on Industrial Electronics* (*ISIE 2011*). Poland, Gdansk 27–30 June, 2011. P.: 761–765. (**IEEE Xplore Digital Library** doi: 10.1109/ISIE.2011. 5984253);
9. **Ose B**., Pugachov V., Orlova S. The Influence of PM's Construction Parameters in Magnetic Coupler on Its Mechanical Torque. *Proceedings of the 6th International Conference on Electrical and Control Technologies* (*ECT 2011*). Lithuania, Kaunas, 4–6 May, 2011. P.: 226–230.

Structure of the Doctoral Thesis

DOCTORAL THESIS BRIEFLY

1. Cylindrical Magnetic Coupler (CMC)

Definition. *Magnetic coupler* (MC) is a machine [13] used to transfer mechanical torque between two or more parts without direct contact using interaction forces of permanent magnets (PMs) induced by their magnetic field. The MCs are manufactured with a sealing screen between the half couplings (Fig. 1.1).

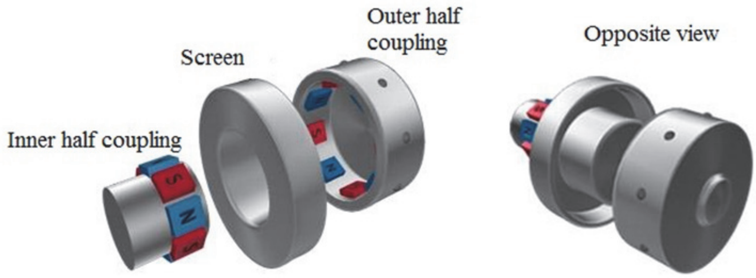

Fig. 1.1 Magnetic coupler

The magnetic coupler (most often) **works this way:** an engine through its shaft rotates the inner half coupling, and because of the attraction and repulsion forces of the PMs between the both half couplings also the outer half coupling starts to rotate. These interaction forces work equally in both ways: when the inner half coupling is driven, the outer half coupling follows, and when the outer half coupling is driven, the inner half coupling follows.

The problem situation with the terminology of *magnetic coupler* and its *half couplings* is provided in the doctoral thesis.

Application. Magnetic couplers are used in different pumps (e.g., centrifugal, gear pump), compressors, liquid (or gaseous/solid substance) mixers, agitators, fans, blowers and autoclaves (usually the reactive MCs). Some application examples are given in Appendix 1 of the doctoral thesis.

Some classifications are provided in the doctoral thesis, e.g., the classification of synchronous and asynchronous clutches (Fig. 1.2) and the MC classification by the magnet interaction surface.

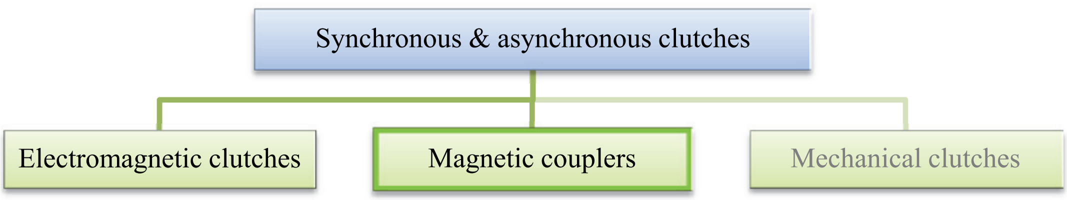

Fig. 1.2 Main groups of synchronous and asynchronous clutches

The design of cylindrical magnetic coupler (CMC) is chosen to be investigated in the doctoral thesis. The main design parameters of CMC with rectangular PMs are (Fig. 1.3): axial length of coupler *l* (mm), inner radius R_1 (mm), PM placement radius of inner half coupling R_2 (mm), PM placement radius of outer half coupling R_3 (mm), outer radius R_4 (mm), air gap δ (mm), PM height h_{PM} (mm), PM width — b_{PM} (mm), yoke height of outer half coupling h_y (mm). Additionally to the given radiuses R_3 and R_4, the yoke height h_y is used, because it changes by (1.1) [18].

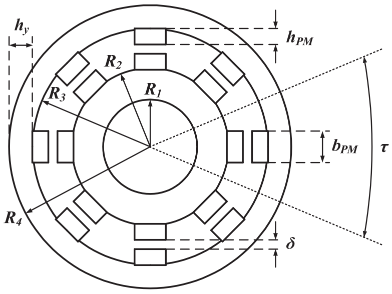

Fig. 1.3 Main design parameters of CMC in cross-section

$$h_y = \frac{\pi R_3 \beta' B_r}{p\, 2\, B_{steel}}, \tag{1.1}$$

where h_y — yoke height in outer half coupling [mm];

R_3 — PM placement radius of outer half coupling [mm];

β' — coefficient that shows which part of a pole pitch τ is covered by PM width b_{PM}: $\beta' = \left(b_{PM}/\tau_{in} + b_{PM}/\tau_{out}\right)/2$;

B_r — PM residual induction [T];

p — pole pair number;

B_{steel} — monitored value of magnetic flux density in yoke [T], chosen B_{steel} = 1.8 T.

The PM material also influences the CMC design. In design calculations, the PM magnetic permeability μ_{PM} is taken into account, acquired from magnet residual induction B_r and coercive force H_c; these values are given in catalogues. In the present research, the relative magnetic permeability of PMs μ_* (1.2) is used [17, 18].

$$\mu_* = \frac{B_r}{H_c \mu_0} = \frac{B_r}{H_c 4\pi 10^{-7}}, \tag{1.2}$$

where μ_* — PM relative magnetic permeability;

B_r — PM residual induction [T];

H_c — PM coercive force [A/m];

μ_0 — magnetic permeability of air and it is $\mu_0 = 4\pi 10^{-7}$ [H/m].

Nowadays the choice of available materials that can be used in CMC manufacturing is very wide, but the following materials are chosen to limit the range of research:

- for PMs — barium ferrite ($BaFe_{12}O_{19}$), strontium ferrite ($SrFe_{12}O_{19}$), samarium cobalt alloy (Sm_2Co_{17}, grade 30H), neodymium iron boron alloy (NdFeB, grade N38UH);
- for a sealing screen — austenitic stainless steel of grade 1.4401 ($\mu_* = 1.004$, but it can be taken as air with $\mu_* = 1.000$);
- for coupler yokes — magnetically soft steel of grade S235JRG2 and material number 1.0038.

Various materials have different magnetic properties. These properties influence the CMC mechanical torque, e.g., curve of mechanical torque for NdFeB ($l = 10$ mm, $R_1 = 10$ mm, $R_6 = 40$ mm, $\beta = 0.9$, $p = 1$, 4 and 8) (Fig. 1.4). As these curves may have unequal form, it is more correct to compare the maximum value of coupler mechanical torque — maximum mechanical torque M_{max}.

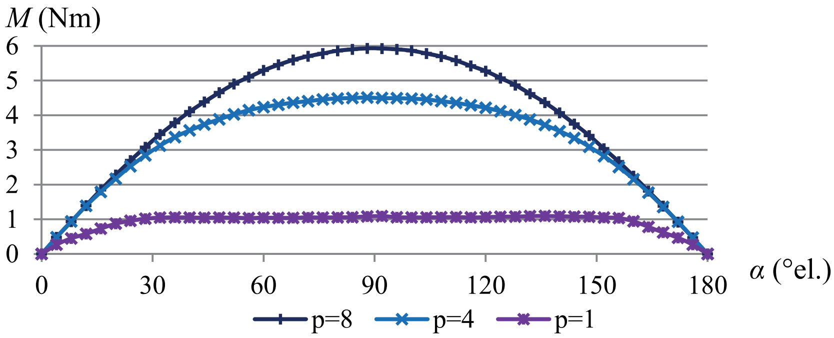

Fig. 1.4 Curves of CMC's mechanical torque (PM made of NdFeB)

The turning angle α at which the mechanical torque has it maximum value M_{max} for couplers with different pole pair numbers p can be calculated by (1.3). The difference in geometric degrees can be seen in Fig. 1.5 (the values of torque are not real, but are scaled).

$$\alpha = \frac{90^\circ}{p}[^\circ\text{geom}] \qquad (1.3)$$

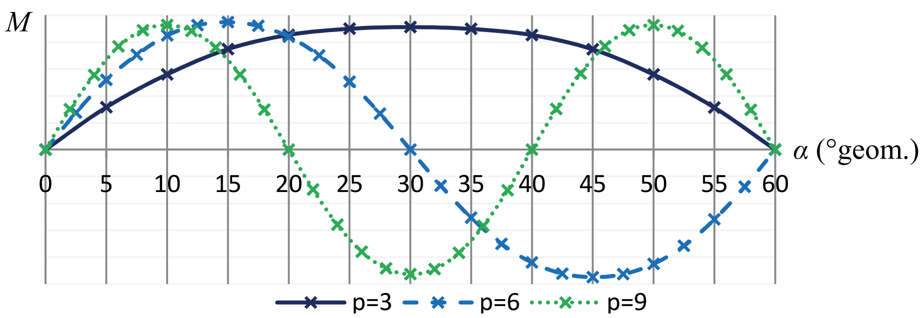

Fig. 1.5 Curves of CMC mechanical torque (PM made of Ba-ferrite)

2. Influence of Design Parameters on Maximum Mechanical Torque of CMC

In this chapter the base CMC is chosen (Fig. 2.1), whose design is optimized. The base model has the rectangular PMs.

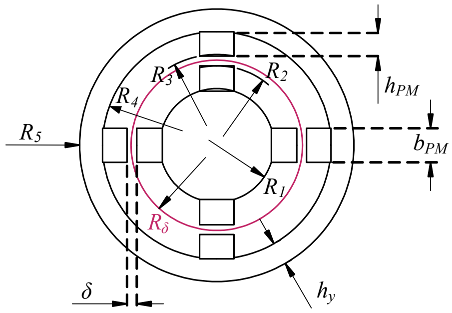

Fig. 2.1 CMC base model with dimensions in cross section

The independent variables are important in optimization, and they are given in Fig. 2.2.

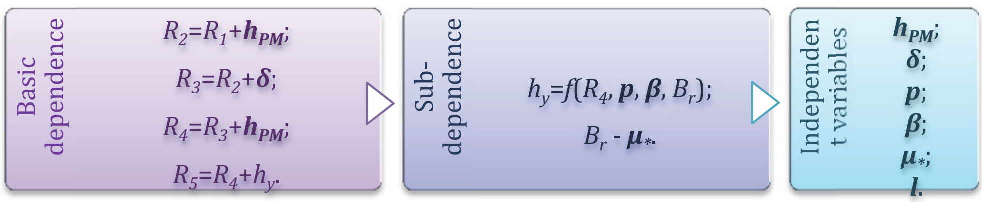

Fig. 2.2 Independent variables from basic dimensions

To model the magnetic field of CMC and calculate the necessary physical values, many kinds of electromagnetic field simulation software can be used, such as *AMPERES* (three dimensional (3D)), *OERSTED* (two dimensional (2D)), *ANSYS Maxwell* (2D/3D), *QuickField* (2D) etc. As the CMC has a symmetrical magnetic field in relation to the axial length, a simpler (two dimensional) electromagnetic field simulation software can be used. In this research the software *QuickField* (*QF*) [14] is applied. This software is based on the finite element analysis.

The full block diagram of developed calculation methodology for obtaining the physical parameters from magnetic field is provided in the doctoral thesis, but the principal steps are shown in Fig. 2.3.

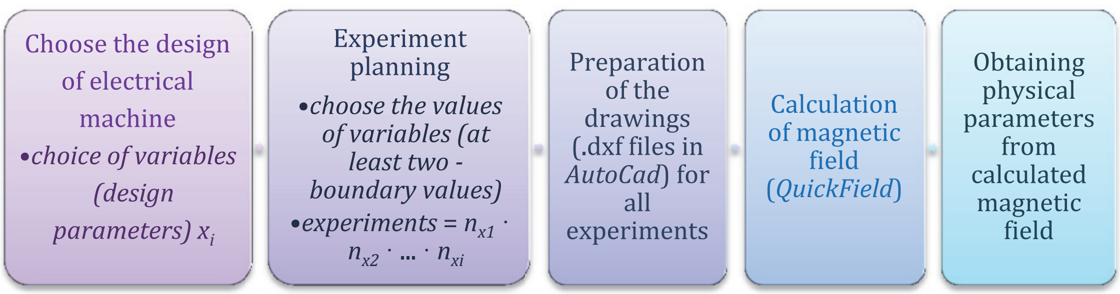

Fig. 2.3 Principal steps of developed calculation methodology

The transition from rectangular PMs to rounded (/sector form) PMs is studied (Fig. 2.4). This transition increases the value of M_{max} by about 35 %. From now the magnetic coverage coefficient β (β = α_{PM}/τ) can be used, where α_{PM} is the angular width of PM (in geometric degrees) and τ is the pole pitch (also in geometric degrees).

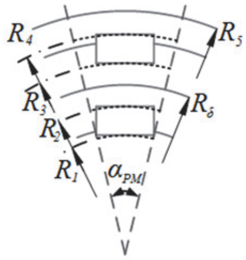

Fig. 2.4 Transition from rectangular to rounded PMs

The present research has also been made with the intention to implement the results in Latvian CMC manufacturer “BTC”. The radius R_1 is stated to be R_1 = 10 mm. The practical implementation is the main reason for all chosen boundary values (Table 2.1).

Table 2.1

Chosen boundary values of variables

Variable	**Minimum value**	**Maximum value**
l (mm)	10	75
P	1	9
B	0.7	0.9
h_{PM} (mm)	4	8
δ (mm)	2	3
μ_*	1.061	1.344

In this chapter the reactive CMC is also studied. When a cylindrical magnetic coupler has the PMs only on one half coupling and the half coupling without magnets has the same toothed form as if the magnets were there, it is called the reactive CMC (Fig. 2.5). Such a design solution is necessary in cases when the environment would be too aggressive to PMs: temperature too high, causing the magnets to noticeably lose their quality — repulsion and attraction forces —, or other influencing factors that could lead to magnet demagnetization, etc.

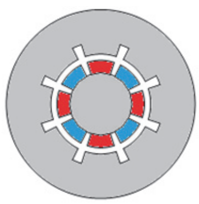

Fig. 2.5 Reactive CMC in cross section

The main disadvantage, why the reactive couplers are used only in case of necessity to transfer the torque in the aggressive environment, is the small value of its maximum mechanical torque, compared with the same design active CMC. Hence, a new design of reactive CMCs (Fig. 2.6) is proposed [11, 12] and studied [8].

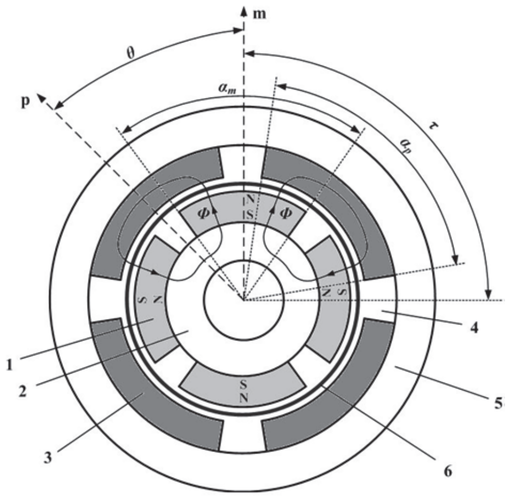

Fig. 2.6 New (patented) design reactive CMC
1 — PMs, 2 — yoke, 3 — sector-shaped poles (ferromagnetic material), 4 — air gap (nonmagnetic material), 5 — body (nonmagnetic & light material), 6 — fixed sealing screen

For the comparison purposes, the characteristic M_{max}/V is chosen — maximum mechanical torque per volume — for objective results, because the new design coupler has a very light nonmagnetic yoke. The PMs are made of NdFeB alloy. The new design reactive coupler has increased M_{max}/V by about 9 times comparing to analogue standard design (with outer yoke) reactive CMC (Fig. 2.7).

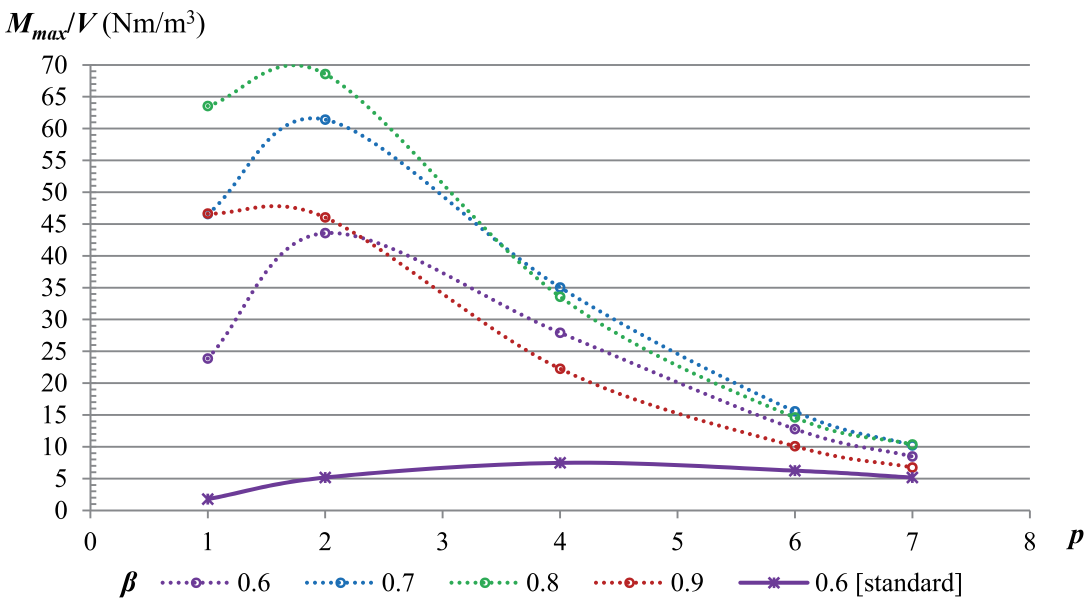

Fig. 2.7 $M_{max} = f(p, \beta)$ for new design reactive CMC

3. Synthesis of Mathematical Models

In multivariate data analysis (MDA), many methods are available [2, 3], but for performing the analysis and creating mathematical models (as formula) the regression analysis is chosen as the most suitable method.

In the *regression analysis* the dependent variable y_1 is quantitative but the independent variables $x_1, ..., x_n$ can be both quantitative and qualitative; the relationship forms as follows:

$$y_1 = f(x_1, x_2, ..., x_n). \tag{3.1}$$

The program complex of formula synthesis has been written by *Dr. sc. ing*. O. Onževs, and it is possible to obtain necessary information about the program and methodology in his doctoral thesis [4].

In the optimization the obtained models or synthesized formulas of objective function and the control parameters are used. The objective function should include the main physical characteristic and some design or economical parameter for an unbiased judgement as in all optimization problems. Thus, the maximum mechanical torque M_{max} is the physical characteristic. The optimization will be made by design parameters and magnet material indirectly indicating the economical aspect — the less material is used, the cheaper the coupler can be made with the characteristic of interest. Thus, as the maximum mechanical torque M_{max} can be the same for most CMCs with a different design parameter combination, the maximum mechanical torque per volume M_{max}/V is chosen as a reliable characteristic.

The objective function is defined as (3.2), but the control parameters are defined as (3.3) just for the rare-earth alloy PMs, and the axial length is not taken as it does not have radical influence on the maximum value of magnetic flux density in the cross section.

$$M_{\max}/V = f(\mu_*; l; h_{PM}; \beta; \delta; p) \tag{3.2}$$

$$B_{\max} = f(h_{PM}; \beta; \delta; p) \tag{3.3}$$

As in the calculation of coupler volume V, the axial length l is included and in the calculation of M_{max} the length l correlates directly. As a result, the axial length l is not taken directly in the formula synthesis for M_{max}/V, because it is already taken into account in M_{max} and V in a direct relation with them ($M_{max}(l)/V(l) \rightarrow M_{max}/V \neq f(l)$). And as the previous studies have shown the best correlation of formulas to experimental data is when separate formulas are synthesized for appropriate PM material; thus, the final objective function is as (3.4).

$$M_{\max}/V = f(h_{PM}; \beta; \delta; p) \tag{3.4}$$

The formula synthesis gives many combinations of elementary functions. The formula is chosen from elimination diagrams, taking into account either the breaking point or the value of correlation.

Analyzing the experiment result, the distribution of pole pair number values is chosen in the formula synthesis, e.g., formula (3.5) of M_{max}/V for coupler with PMs made of samarium-cobalt alloy and for pole pair numbers p = 7−9 (correlation is ρ = 95.37 %), and formula (3.6) of $B_{max\ in}$ for coupler with PMs made of rare-earth alloys and for pole pair numbers p = 2, 3 (correlation is ρ = 80.40 %).

$$M_{\max}/V = -50.0 + 102.2\frac{h_{PM}}{\delta} - 10.46p - 20.17h_{PM} + 362.3\beta - 19.93\frac{h_{PM}^2}{\delta^2} + \\ + 0.880h_{PM}^2 - 212.1\beta^2 + 1.66\frac{h_{PM}^3}{\delta^3}. \quad (3.5)$$

$$B_{\max in} = 2.532 + 0.0913p - 5.11\beta + 0.125h_{PM} - 0.033h_{PM} \cdot p + 0.036\frac{h_{PM}}{\delta} + 4.121\beta^2, \quad (3.6)$$

The synthesized formulas are tested, and the results show that the separation of PM materials and pole pair numbers have been appropriate and the relative error for the main characteristic M_{max}/V is $\varepsilon_{M/V}$ < 5 % and for the control parameters B_{max} it is ε_B < 10 %, acquiring valid mathematical (in formula form) models.

4. Optimization of CMC

The optimization problem is discrete and constrained. Though many optimization algorithms (such as gradient method, interval bisection method, Powell's quadratic interpolation etc.) are overviewed, it is decided to use an existing optimization tool. Many multivariate data analysis and optimization software tools are available, some of them are overviewed and the *SIMCA* is chosen.

Applying *SIMCA*, the optimum is found. Of course, the optimum is when PMs are made of rare-earth alloy instead of simple ferrite. If the material types are taken separately the following optimization results are obtained:

- For rare-earth alloys with M_{max}/V = 172.27 (Nm/m^3) and M_{max} = 36.97 (Nm):
  - ✓ Relative permeability μ_* = 1.061 (NdFeB);
  - ✓ Axial length l = 75 mm;
  - ✓ Pole pair number p = 5;
  - ✓ Magnetic coverage coefficient β = 0.80;
  - ✓ PM height h_{PM} = 8 mm;
  - ✓ Air gap δ = 2 mm;
- For simple ferrites with M_{max}/V = 14.64 (Nm/m^3) and M_{max} = 3.09 (Nm):
  - ✓ Relative permeability μ_* = 1.344 (Sr-ferrite);
  - ✓ Axial length l = 75 mm;

- ✓ Pole pair number $p = 4$;
- ✓ Magnetic coverage coefficient $\beta = 0.80$;
- ✓ PM height $h_{PM} = 8$ mm;
- ✓ Air gap $\delta = 2$ mm.

The made optimization allows developing the optimization methodology for CMCs, the main steps of which are shown in Fig. 4.1.

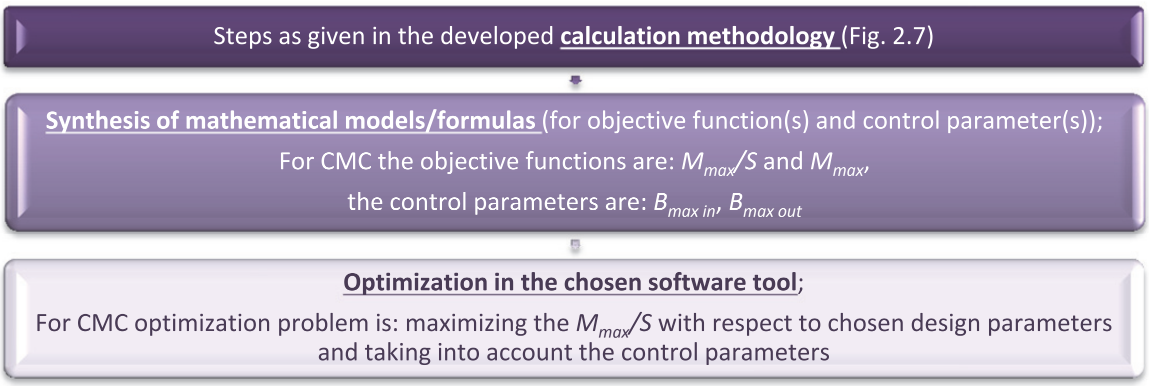

Fig. 4.1 Main steps of developed optimization methodology

5. Experiments and Further Research Possibilities

In this chapter, the experiments and the author's opinion of further research possibilities for CMC design optimization are given.

The first set of experiments is made to obtain the mechanical torque curve of CMC and compare it with the one calculated in *QuickField* (*QF*). A specifically designed object with implemented CMC was made to obtain the experimental curve of mechanical torque (Fig. 5.1). The whole object is made on the foot stand 1; thus, it is portable and can be fixed at any stand. CMC 3 has inner and outer half couplings with rectangular permanent magnets. The inner half coupling is turned by an angle by the rotation axis 2.

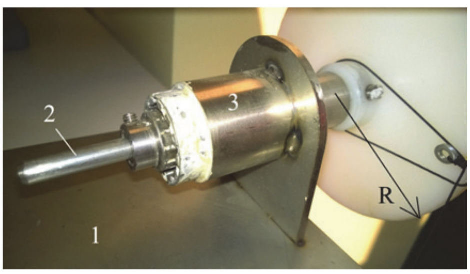

Fig. 5.1 The prepared object with implemented CMC for the experiment (back side)

The CMC has NdFeB magnets, and the pole pair number is $p = 6$. Other design parameters are given in the doctoral thesis — description of the coupler BR-5 (Section *2.1.3*).

Method of traditional experiment is the work principle of Dynamometer: by knowing the radius and added weight (or force), the torque can be calculated. For chosen angles α_i the mass m_i is known, which has to be added to balance out the torque in the air gap between the half couplings, and the radius R is known (R = 56 mm). The torque value M_i is calculated by (5.1.) at the certain turning angle α_i.

$$M_i = R \cdot F_i = 0.056 \cdot g m_i \,(\mathrm{Nm}) \tag{5.1}$$

For the same coupler BR-5 the drawing is prepared and its torque is calculated in *QF*. The results are compared (Fig. 5.2). As in the optimization the maximum value of mechanical torque is used, these values are separately compared: $M_{max\ exp}$ = 0.623 Nm and $M_{max\ QF}$ = 0.591 Nm. The difference is ΔM_{max} = 0.032 Nm or 5.4 % (according to M_{max} = 0.591 Nm). These results verify that the *QuickField* software is permissible for obtaining the mechanical torque maximum values (/developed calculation methodology is applicable) to be used further in CMC design optimization.

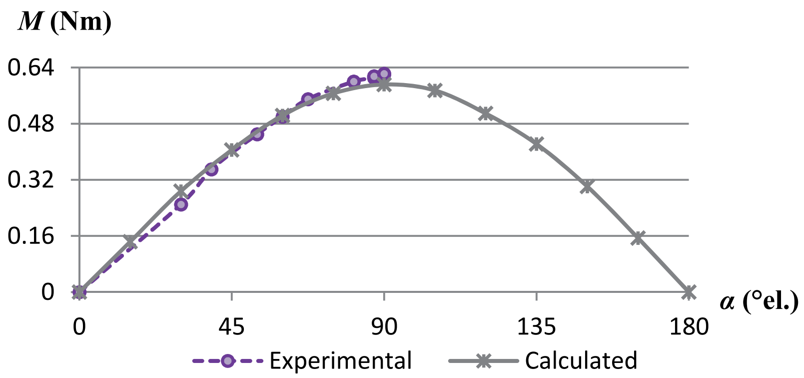

Fig. 5.2 Mechanical torque of CMC BR-5

The second set of experiments is made to obtain the mechanical torque curve of CMC and compare its maximum value with the one calculated by synthesized formula (/created mathematical model). Again, a specifically designed object with implemented CMC was made to obtain the experimental curve of mechanical torque (Fig. 5.3). The whole object is made on the foot stand 1; thus, it is portable and can be fixed at any stand. CMC 2 has inner and outer half couplings with rounded permanent magnets. To hold the coupler inner half coupling in one position, an added weight 3 is needed.

The CMC has rounded (/sector form) NdFeB magnets with pole pair number p = 5, height h_{PM} = 9.5 mm and magnetic coverage coefficient β = 0.95. The axial length is l = 76.2 mm and air gap is δ = 4.3 mm. The radiuses are: R_1 = 17.75 mm and R_5 = 50.85 mm (Fig. 2.1).

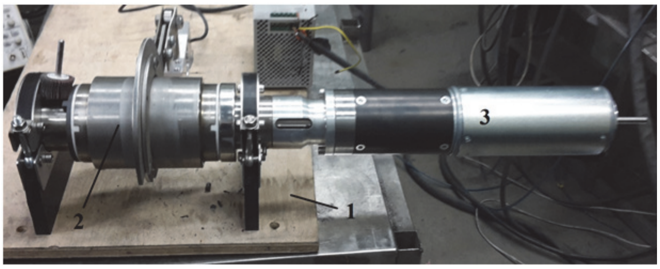

Fig. 5.3 The prepared object for the experiment

Method of classical experiment — the torque values are obtained at certain angles similar to work principle of Dynamometer: by knowing the radius and added force, the torque is calculated by oscilloscope. The curve of mechanical torque is obtained in the oscilloscope, where the certain values of the turning angle α_i (given by voltage sensor) and the force F_i are used to calculate the torque value M_i (5.2). When the outer half coupling tries to rotate, the pressure force F is made by the arm of force l' = 200 mm (= 0.20 m) and it is measured by the sensor (of pressure force). The stand for obtaining the mechanical torque in the experimental way is given in Fig. 5.4. Only the maximum value of mechanical torque M_{max} is taken and it is M_{max} = 76.13 Nm.

$$M_i = l' \cdot F_i \ (\mathrm{Nm}) \qquad (5.2)$$

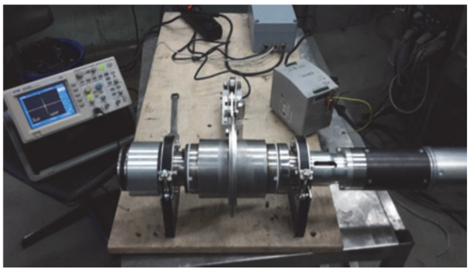

Fig. 5.4 The whole stand of experiment

In this case to forecast the maximum value of mechanical torque a separated formula is synthesized (5.3). The modelled design of CMC is simpler because the magnet material is NdFeB (μ_*-const), magnetic coverage coefficient is β = 0.95 (also constant) and the air gap is also known (δ = 4.3 mm).

The formula is true for models with the following variable ranges: l = 70–80 mm, h_{PM} = 8–10 mm and p = 4–6. The ranges are small, but the result calculated with formula should be precise.

$$M_{\max} = l \cdot \left(0.3 + 0.09 h_{PM} - 0.007 h_{PM} \cdot p + 0.0023 h_{PM}^2\right) \qquad (5.3)$$

Inserting the variables p = 5, h_{PM} = 9.5 (mm) and l = 76.2 (mm), the value of maximum mechanical torque is M_{max} = 78.492 Nm.

If the value obtained experimentally is taken as the basic one, then for M_{max} calculated by (5.3) the absolute error is ΔM_{max} = 2.36 Nm and the relative error is ΔM_{max} = 3.1 %. Hence, it can be concluded that the developed formula (/mathematical model) based on the multivariate regression analysis is a very useful tool in the forecasting of M_{max} values and, thus, the formulas can be used in the optimization problems.

Main Conclusions

The analysis of latest studies on the cylindrical magnetic coupler (CMC) proves that the research of influencing design parameters and the optimization of CMC design based on magnetic field calculations made within the present doctoral thesis has not been performed yet.

As the main characteristic of CMC the maximum mechanical torque M_{max} is chosen because the curves of mechanical torque M for different couplers may vary by amplitude and period. To avoid the mistakes that appear in an inappropriate comparison, one characterizing value (M_{max}) from the whole torque curve is taken. The CMC has many design parameters, but only 5 (pole pair number p, magnetic coverage coefficient β, PM height h_{PM}, air gap δ and axial length l) are chosen to be optimized. The 6th parameter is relative permeability μ_* characterizing the material of which the permanent magnets (PMs) are made; this parameter also indirectly influences the CMC design and its main characteristic M_{max}. For these parameters the boundary values are studied and consequently chosen.

The base design is the CMC with rectangular PMs. The offered transition from rectangular PMs to rounded (or sector form) ones enables the improvement of M_{max} by more than 30 %. The optimization is made for the CMC with rounded PMs. As the values of M_{max} can be equal or very similar to couplers with very different design parameters, the characteristic as maximum torque per volume M_{max}/V is taken.

The calculation methodology is developed to obtain the desired parameters: main characteristic M_{max} and the control parameters — maximum values of magnetic flux density in inner and outer half coupling yokes — $B_{max\ in}$ and $B_{max\ out}$. The developed methodology includes the application of *AutoCad* drawing software and *QuicField* (*QF*) magnetic field modelling software.

The reactive CMC is also studied and a new patented design is developed having improved M_{max} by 2 times and M_{max}/V by about 9 times when compared with the analogue (/standard design reactive CMC with yoke of outer half coupling) reactive CMC.

The optimum of reactive CMC can be found only by developed calculation methodology without any further mathematical procedures.

For the set boundaries and defined objective function completely new CMC design models/formulas are synthesized, out of which the most appropriate ones are chosen. The testing of these models proves that the precision is high: less than 5 % for M_{max}/V and less than 10 % for B_{max}.

The optimization algorithms are analyzed and the *SIMCA* optimization tool is chosen. The optimization process proves that M_{max}/S (maximum mechanical torque per area) will be more correct to use in the optimization instead of M_{max}/V. The first step in the optimization problem is the maximization of M_{max}/V with the respect to chosen variables (design parameters), and, as more than one optimum is found, the sub-problem is the maximization of M_{max} with respect to the one left variable — axial length. The optimum is found and it (with $\boldsymbol{M_{max}/V}$ **= 172.27** Nm/m^3 and $\boldsymbol{M_{max}}$ **= 36.97** Nm) is following: **μ_* = 1.061**, **p = 5**, **β = 0.8**, **l = 75** mm, **h_{PM} = 8** mm, and **δ = 2** mm.

When the coupler optimization system is reduced to the following — coupler with magnets made of simple ferrites —, the optimum point with $\boldsymbol{M_{max}/V}$ **= 14.67** (Nm/m^3) and $\boldsymbol{M_{max}}$ **= 3.09** (Nm) is the following: **μ_* = 1.344**, **p = 4**, **β = 0.8**, **l = 75** mm, **h_{PM} = 8** mm, and **δ = 2** mm.

The performed studies and optimization of active CMC allow developing a new optimization methodology.

The first set of experiments is the acquisition of the CMC (with rectangular PMs) torque. The first experiment is made by the method based on Dynamometer working principle, and the torque of the same coupler is obtained applying the *QF* software. The results are compared and it is concluded that the software can be used for the curve of torque (and other necessary parameter) acquisition, having the error of less than 6 per cent. Thus, the developed methodology of M_{max} and B_{max} acquisition is correct.

The second set of experiments is the acquisition of maximum value of CMC (with rounded PMs) torque. The torque maximum value from the first experiment is compared with the value obtained by the synthesized model/formula. The results demonstrate that the use of synthesized models can be a very useful way for forecasting M_{max}, having the error of less than 5 %.

A new optimization methodology is proposed for obtaining the optimal combination of CMC design parameters, and it is the following: start with obtaining the necessary physical parameters depending on the chosen design parameters by the magnetic field calculations; next step is the synthesis of mathematical models/formulas (based on results from calculations of magnetic field) which allow forecasting the chosen characteristics such as M_{max} and M_{max}/S; the last step includes the choice of optimization tool and the coupler optimization.

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