# Design optimization of APMEC using chaos multi-objective particle swarm optimization algorithm

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ABSTRACT

In order to meet the requirement that the permanent magnet eddy current coupler has larger [*output torque*](https://www.sciencedirect.com/topics/engineering/output-torque) and [*smaller eddy*](https://www.sciencedirect.com/topics/engineering/smaller-eddy) current loss in actual operation, the structural parameters and operation performance of axial permanent magnet eddy current coupler (APMEC) are optimized by chaos multi-objective [*particle swarm optimization*](https://www.sciencedirect.com/topics/engineering/particle-swarm-optimization) algorithm (CMOPSO) in this paper. The model of APMEC is established by three-dimensional [*finite element simulation*](https://www.sciencedirect.com/topics/engineering/finite-element-simulation). The [*central composite design*](https://www.sciencedirect.com/topics/engineering/central-composite-design) (CCD) method is used to select the appropriate test point, and the response value is obtained by ANSYS finite element analysis software simulation. The second-order response surface regression model of APMEC was established according to the response value. The CMOPSO is used to optimize APMEC, and the optimal combination of structural parameters is obtained. By comparing the eddy current density distribution of APMEC before and after optimization with the finite element simulation experiment, it is verified that the optimization method is feasible to optimize the structural parameters of APMEC. The optimization results show that the efficiency of the permanent magnet eddy current coupler is more than 94%, and the energy consumption is reduced to 83% of the original energy consumption.

**Keywords**—Axial permanent magnet eddy current coupler; Finite element method (FEM); Response surface methodology (RSM); Chaos multi-objective particle swarm optimization algorithm.

# 1.INTRODUCTION

Permanent magnet eddy current coupler (PMEC) is a new type of high efficiency transmission device. In recent years, the PMEC has made a breakthrough progress in efficiency and manufacturing. But the optimization of its structure parameters and operation performance needs further study. Different optimization methods aiming at the single performance of PMEC have been gradually applied. However, the advantages and disadvantages of other performance are not considered, so the performance optimization is not comprehensive. The influence of the structure parameters of PMEC on its performance has been studied and verified by many scholars by means of analytical method, numerical method and experimental analysis [[1]](https://www.sciencedirect.com/science/article/pii/S2352484721006090#b1), [[2]](https://www.sciencedirect.com/science/article/pii/S2352484721006090#b2), [[3]](https://www.sciencedirect.com/science/article/pii/S2352484721006090#b3), [[4]](https://www.sciencedirect.com/science/article/pii/S2352484721006090#b4). Therefore, it is important to study the optimization method of PMEC and find the best structural parameters. The structure parameters of PMEC are optimized by [genetic algorithm](https://www.sciencedirect.com/topics/engineering/genetic-algorithm) in literature [[5]](https://www.sciencedirect.com/science/article/pii/S2352484721006090#b5). However, only the influence of structure parameters on [output torque](https://www.sciencedirect.com/topics/engineering/output-torque) is considered, and other performances are not optimized. In [[6]](https://www.sciencedirect.com/science/article/pii/S2352484721006090#b6), [particle swarm optimization](https://www.sciencedirect.com/topics/engineering/particle-swarm-optimization) (PSO) combined with simplex method was used to optimize the cost objective of permanent magnet eddy current coupler.Grushevenko [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib146)). However, widespread adoption requires more than economic competitiveness, especially for personally owned vehicles. Behavioral and non-financial preferences of individuals on different technologies and mobility options are also important (Lavieri et al [2017](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib161), Li et al [2017](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib170), McCollum et al [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib189), Ramea et al [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib250)). EV adoption beyond LDVs has been focused on buses, with significant adoption in several regions (especially China). Electric trucks also are receiving great attention, and Bloomberg New Energy Finance (BloombergNEF) projects that by 2025, alternative fuels will compete with, or outcompete, diesel in long-haul trucking applications (Moore and Bullard [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib199)). These recent successes are being driven by technological progress, especially in batteries and power electronics, greater availability of charging infrastructure, policy support driven by environmental benefits, and consumer acceptance. EV adoption is engendering a virtuous circle of technology improvements and cost reductions that is enabled and constrained by positive feedbacks arising from scale and learning by doing, research and development, charging-infrastructure coverage and utilization, and consumer experience and familiarity with EVs.

# 2. Structure and finite element modeling of APMEC

**2.1. Structure of APMEC**

The structure of two-group APMEC is shown in [Fig. 1](https://www.sciencedirect.com/science/article/pii/S2352484721006090#fig1) [[7]](https://www.sciencedirect.com/science/article/pii/S2352484721006090#b7). The permanent magnet is magnetized along the [axial direction](https://www.sciencedirect.com/topics/engineering/axial-direction), and the N and S poles are alternately placed. When there is slip between the copper plate and the steel plate of the permanent magnet, the induced current is generated on the surface of the copper plate, and then the induced magnetic field is generated. The interaction between the induced magnetic field and the permanent magnetic field produces a coupling force, so as to realize the effect of transfer torque.

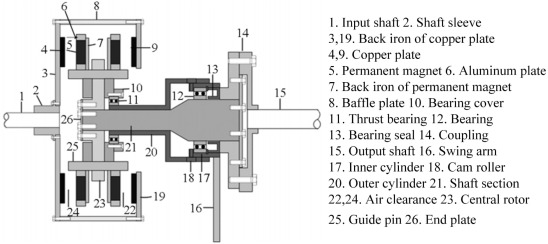


Fig. 1. Mechanical structure of APMEC.

**2.2. Finite element modeling of APMEC**

ANSYS [finite element simulation](https://www.sciencedirect.com/topics/engineering/finite-element-simulation) software is used to establish the three-dimensional [motion eddy](https://www.sciencedirect.com/topics/engineering/eddy-motion) current field finite element model of APMEC in this paper. Considering that PMEC is a typical [axisymmetric](https://www.sciencedirect.com/topics/engineering/axisymmetric) structure, the model established in this paper is only half of the actual model. The following assumptions should be made in the simulation:

* Ignoring the [elastic deformation](https://www.sciencedirect.com/topics/engineering/elastic-deformation) of copper plate and permanent magnet
* Ignoring the influence of temperature on material properties

The main structural parameters of the prototype are as follows: the inner radius of the copper plate is 190 mm, the outer radius is 370 mm, and the thickness is 7 mm; the radial height of the permanent magnet is 94 mm, the radial width is 130 mm, the axial thickness is 20 mm; the number of magnetic poles is 12; the average air gap thickness is 4 mm; and the relative slip between copper disk and permanent magnet disk is 45 r/min. According to the above parameters, the finite element simulation model of permanent magnet eddy current coupler is shown in [Fig. 2](https://www.sciencedirect.com/science/article/pii/S2352484721006090#fig2). The [output torque](https://www.sciencedirect.com/topics/engineering/output-torque) and [eddy current loss](https://www.sciencedirect.com/topics/engineering/eddy-current-loss) of the finite element model are 3223.2 N m and 17.2613 kW, respectively.

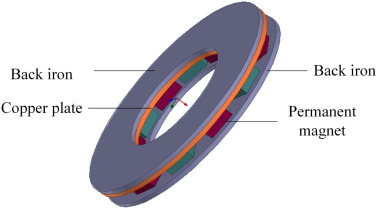


Fig. 2. Simulation model of APMEC.

# ****3.  Response surface methodology (RSM) model of APMEC****

It is difficult to obtain the functional relationship between the structural parameters of APMEC and its output torque, eddy current loss and other response variables. The output torque and eddy current loss of APMEC with different structural parameters can be obtained by ANSYS [finite element simulation](https://www.sciencedirect.com/topics/engineering/finite-element-simulation). Therefore, before the parameter optimization, it is necessary to select the appropriate test point through the [central composite design](https://www.sciencedirect.com/topics/engineering/central-composite-design) (CCD). Then the input and output sample data are obtained by finite element modeling. Finally, according to the output response value, the second-order response surface regression model of APMEC response variable and design variable is established. Among them, the design variables are the main structural parameters affecting the performance of APMEC, including the copper plate thickness, the permanent magnet, thickness, the relative slip and the air gap width. The response variables are the output torque and eddy current loss of APMEC.

**3.1. Central composite design (CCD)**

In this paper, central composite face-centered design (CCF) of CCD method is used for [experimental design](https://www.sciencedirect.com/topics/engineering/design-of-experiments). The CCD method only makes numerical experiments at the central point and its extension point, which can provide a lot of information about test variables and test errors with the least working cycle. There are three level values (−1, 0, 1) for each design variable in CCF method. Where −1 is the lower boundary value of the design variable, 1 is the upper boundary value, and 0 is the average value of the upper and lower boundaries. [Table 1](https://www.sciencedirect.com/science/article/pii/S2352484721006090#tbl1) shows the level of design variables:

The CCD was carried out according to the four selected design variables. The output torque and eddy current loss power of APMEC with different combination structure parameters can be obtained by modifying the corresponding parameters of the finite element model and using ANSYS software simulation. The experimental results were used to establish the second-order [regression equation](https://www.sciencedirect.com/topics/engineering/regression-equation) of two response variables by RSM.

**Table 1. The factor level of the design parameters.**

| **Design parameters level** | **Copper plate thickness/mm** | **Permanent magnet thickness/mm** | **Relative speed/(r/min)** | **Air gap width/mm** |
| --- | --- | --- | --- | --- |
| −1 | 4 | 20 | 35 | 3 |
| 0 | 6 | 30 | 50 | 6 |
| 1 | 8 | 40 | 65 | 9 |

### **3.2. CMOPSO of APMEC**

In this paper, chaos optimization is introduced into MOPSO to optimize the structure parameters and operation performance of APMEC. The specific steps of the algorithm are as follows:

* Initialization. According to the random value of uniform probability, the positions of all particles are obtained in the decision space, and the velocity of particles is 0. The optimal initial position is the individual of the particle, and the outer set is empty.
* Population evaluation. According to the range of objective function, the particles are evenly divided into 300 [meshes](https://www.sciencedirect.com/topics/engineering/meshes).
* Individual optimization of update particles. When the particle’s individual optimum is dominated by the current target value vector or not, the individual optimum is updated to the particle’s current position, otherwise the original individual optimum is maintained.
* Non-dominated set construction. After deleting the particles that do not meet the dominant condition, they are merged with the external set.
* External set update. When the number of solutions in the outer set is larger than its carrying capacity, the crowding distance method prunes the outer set.
* Termination condition judgment. When the number of iterations is more than 200, stop searching and output the file set; when the number of iterations is less than 200, turn to next step.
* The particles with the smallest mesh density are recorded as global guides. When there are multiple particles, one of them is selected randomly. Then turn to step population evaluation.

After optimization, the [Pareto curve](https://www.sciencedirect.com/topics/engineering/pareto-curve) is drawn with the solution set, as shown in [Fig. 3](https://www.sciencedirect.com/science/article/pii/S2352484721006090#fig3). The points satisfying the constraint conditions are selected on the curve to obtain the final optimal solution of structural parameters.

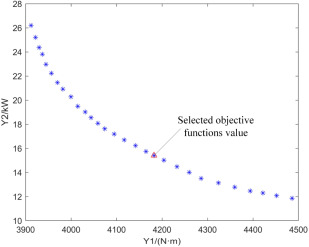


Fig. 3. [Pareto curve](https://www.sciencedirect.com/topics/engineering/pareto-curve) for multi objective optimization.

### **4.1. Simulation analysis of optimization results**

The results show that the thickness of copper plate is 6 mm, the thickness of permanent magnet is 30 mm, the relative slip is 35 r/min, and the air gap width is 3 mm. [Table 2](https://www.sciencedirect.com/science/article/pii/S2352484721006090#tbl2) compares the structure parameters and operation performance of the APMEC before optimization, using ordinary MOPSO results and using CMOPSO results

ANSYS finite element software is used to establish the model of permanent magnet eddy current coupler before and after optimization. The output torque and eddy current loss of APMEC before and after optimization are calculated. When the permanent magnet eddy current coupling operates stably, the optimized working efficiency can reach more than 94%, and the energy consumption of the permanent magnet actuator is reduced to 83% of the original energy consumption. When the optimal parameters are selected, the output torque of APMEC can be larger when the eddy current loss is smaller. The data in [Table 2](https://www.sciencedirect.com/science/article/pii/S2352484721006090#tbl2) shows that the search results of the optimization algorithm are reliable and effective.

Table 2. The parameters of non-optimized and optimized APMEC.

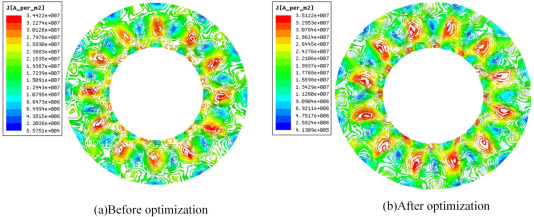
| **Parameter** | **Before optimization** | **CMOPSO** | **Ordinary MOPSO** |
| --- | --- | --- | --- |
| Copper plate thickness/mm | 7 | 6 | 8 |
| Permanent magnet thickness/mm | 20 | 30 | 25 |
| Relative speed/(r/min) | 45 | 35 | 40 |
| Air gap width/mm | 4 | 3 | 3 |
| Output torque/(N m) | 3223.2 | 3882.2 | 3701.5 |
| Eddy current loss/kW | 17.2613 | 14.3136 | 15.4076 |

The finite element model of APMEC can also get the eddy current density distribution map before and after optimization, as shown in [Fig. 4](https://www.sciencedirect.com/science/article/pii/S2352484721006090#fig4). It can be seen that the optimized eddy current distribution is more concentrated. Because the output torque of APMEC is positively correlated with the eddy current generated by copper plate, the output torque of optimized APMEC increases significantly, which is more conducive to the improvement of efficiency. From the above distribution map and the data in [Table 2](https://www.sciencedirect.com/science/article/pii/S2352484721006090#tbl2), it can be seen that the optimization algorithm proposed in this paper can find out the optimal value of the parameters in the range of values.

**5. Conclusion**

In this paper, a second-order response surface regression model of APMEC is established by combining finite element method (FEM), central composite design (CCD) and response surface methodology (RSM). The CMOPSO is applied to the multi-objective optimization of structural parameters and operation performance of APMEC. The optimization results show that the optimization effect is better than that of the traditional method. Finally, through ANSYS finite element simulation experiment, the eddy current density of APMEC before and after the improvement is compared, and the feasibility of the optimization method is verified.

The optimization method proposed in this paper further improves the work efficiency of the system and reduces the energy consumption, which is of great significance to real energy saving. Next, the optimization method can be introduced into the optimization of permanent magnet eddy current couplers with other structures, and other suitable optimization algorithms can be studied.



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