



TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 68, Issue Special I, May, 2025

STUDIES ON THE DESIGN AND PERFORMANCE OF A MAGNETIC PLANETARY GEAR

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Abstract: *Magnetic gears are innovative devices that emulate the functionality of traditional mechanical gears using magnetic fields instead of physical contact between teeth. The subject of our concerns is the study of the performances and design elements for a planetary magnetic gear. The originality of the proposed magnetic gear lies in the fact that the arrangement of the gears and the geometric shape of the teeth allow, at the limit, mechanical engagement. The problem that arises is to determine as precisely as possible the torque capable of being transmitted at the level of two teeth and then by extrapolation, the torque capable at the level of the planetary magnetic gear can be determined.*

Keywords: *planetary magnetic gear, torque transfer, torque density, analysis of variance*

1. INTRODUCTION

Magnetic gears are innovative devices that emulate the functionality of traditional mechanical gears using magnetic fields instead of physical contact between teeth. They convert the principles of torque transmission and speed modulation from mechanical systems into a contactless, magnetically driven mechanism.

The idea of a magnetic gear can be traced back to a patent from 1901 [1]. The object of the invention, as described, is to provide a device whereby power may be transmitted from one shaft to another by a means employing magnetic lines of force, and as a result, the operation of the said device is noiseless, efficient, and easily controlled. Another patent [2] has as object to provide a magnetic or electro-magnetic coupling for two shafts, which is adjustable so that the shafts will rotate, in the same or opposite directions. The specific name of magnetic gearing can be identified in the patent [3]. In carrying object of invention into effect are used magnetic gears in which the teeth-are permanent magnets and the driving forces are transmitted by repulsion of magnetic forces produced by such magnets.

Over time, various other ideas regarding magnetic gears have been patented [4-8].

Analysis studies and reviews are published at conferences or in scientific journals with reference to magnetic gears [9-16].

Doctoral research on the subject can also be mentioned [17-19].

From the study of literature, several ideas can be formulated to organize the multitude of knowledge, as follows:

1. Magnetic gears can be classified based on topology (coaxial, axial, linear, planetary), coupling mechanism (permanent magnet, hybrid, reluctance-based), application (industrial, automotive, aerospace, medical).

2. The performances of magnetic gears are analyzed by:

- Calculate key performance metrics (torque transmission and torque density; efficiency - above 95% in most designs; speed ratio and gear ratio).
- Evaluate losses (eddy currents and hysteresis losses impact efficiency; leakage flux and saturation reduce effective torque).
- Use simulation and testing (FEA simulations predict magnetic behavior, experimental validation ensures real-world accuracy).

- Compare with mechanical gears (magnetic gears offer advantages in durability, noise reduction, and overload protection).

3. There are concerns in the industrial, research and academic environment regarding magnetic gears that can be summarized as in Table 1.

Table 1

Current Concerns and Solutions.

Concern	Issue	Potential Solutions
Torque Density	Lower than mechanical gears	Higher pole-pair ratio, optimized topology
Demagnetization	Heat and overload reduce efficiency	Use SmCo magnets, active cooling
Magnetic Leakage	Reduces torque transfer	High-permeability materials, optimized air gaps
Rare-Earth Magnet Costs	High cost & supply chain risks	Alternative materials, hybrid magnet systems
Complex Manufacturing	Requires precision alignment	Additive manufacturing, automation
External Magnetic Interference	Affects torque stability	Magnetic shielding, closed flux designs
High-Speed Efficiency Losses	Eddy currents & hysteresis increase at high revolutions	Laminated cores, flux optimization
Industrial Adoption	Mechanical gears are more trusted	Standardization, awareness campaigns

In the context structured above regarding magnetic gears, our concerns are in the area of converted topology, more precisely planetary magnetic gears, and for production we use additive manufacturing.

2. DESCRIPTION OF THE RESEARCH PROBLEM

The subject of our concerns is the study of the performances and design elements for a planetary magnetic gear. For this purpose, we designed and manufactured a planetary magnetic gear, as can be seen in Figure 1, consisting of body 1, on which a sun.

gear wheel 2 is mounted that drives three other gears (planet gears) 3, the movement being transmitted to a ring gear 4, the entire assembly

being able to be driven by an electric motor 5 controlled through an electronic interface that allows different dynamic experiments (speed variation, accelerations, etc.).

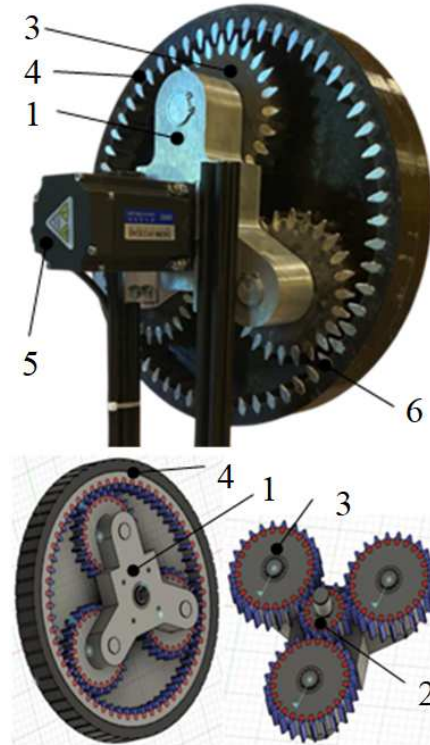


Fig. 1. View of magnetic planetary gear system developed.

The constructive elements of the assembly were developed by the 3D printing technological method, and the magnetic tooth 6, by sintering from Nd2Fe14B magnetic material. The geometric shape and the magnetization mode of the magnetic tooth are presented in Figure 2.

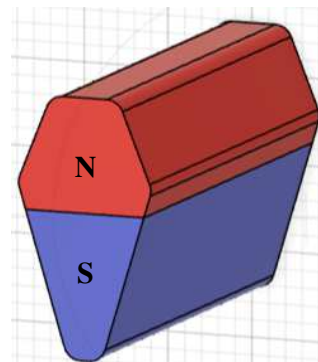


Fig. 2. Magnetic tooth and polarization mode.

The originality of the proposed magnetic gear lies in the fact that the arrangement of the gears

and the geometric shape of the teeth allow, at the limit, mechanical engagement. More explicitly: if the torque capable of being transmitted magnetically is exceeded, i.e. the teeth come into contact, the transmission of motion continues through contact engagement.

The problem that arises is to determine as precisely as possible the torque capable of being transmitted magnetically at the level of contact between two teeth and then, by extrapolation, the torque capable at the level of the planetary magnetic gear can be determined.

3. RESEARCH METHOD

Setting up a research method involves going through several steps, as described below.

3.1 Process Analysis

The contact between two teeth, two gears, involves at least two factors: the width of the contact and the distance between the axes of the gears, which determines the height of the contact between the teeth. If we assign the width of the contact to Factor A, and the height of the contact to Factor B, we could study the process from a systemic perspective, as shown in Figure 3.

The response is the torque capable of being transmitted between the two wheels, at the level of interaction between two teeth.

From the perspective of Factor A, the contact width, three levels of interaction can be considered: full-length interaction, half-length interaction, and one-third-length interaction.

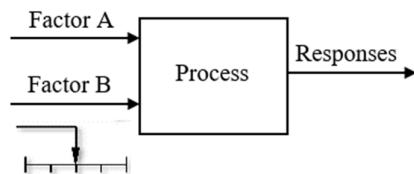


Fig. 3. The process as an IN-OUT system.

An explanation of how the levels of Factor A were chosen is presented in Figure 4.

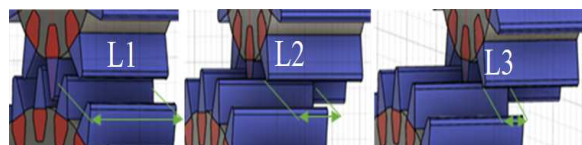


Fig. 4. Explanation of how levels for factor A were chosen.

From the perspective of Factor B, the distance between the wheel axles, which determines the height of contact between the teeth, three levels of interaction can also be considered, as shown in Figure 5.

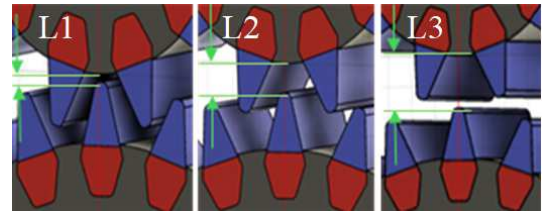


Fig. 5. Explanation of how levels for factor B were chosen.

The level values for Factor A and Factor B are presented in Table 2.

Table 2

Factor levels and difficulty adjusting the factor.

Factors	Level Factors			Degree of difficulty in regulating the level of the factor
	Level 1	Level 2	Level 3	
A[mm]	25	12.5	8.3	OOO
B [mm]	88	84	82	OO

3.2 The layout for conducting experiments

To carry out the experiments, a test layout was configured as shown in Figure 6.

The layout allows the mounting of two gears with magnetic teeth, 1 and 2, on two parallel axes. An adjustment lever 3 allows the vertical movement of the gear 1, ensuring the possibility of adjusting the distance between the axes of the two wheels, i.e. the Factor B. Two translation tables adjusted by the displacement/adjustment screws 4 and 5 ensure the movement on the horizontal axes, thus allowing the adjustment of the levels for the factor A. A dynamometer 6 allows the measurement of the torque transmitted by a lever 7. To create resistance, the wheel 1 is blocked by the lever 8. The torque is measured when an electronic multimeter 9 signals the contact between the teeth.

3.3 Defining the model

The model has two factors, each considered with 3 levels. A fractional experimental design

was chosen and a linear model with 5 degrees of freedom was chosen as follows:

$$Y \cong \bar{X} + A + B \quad (1)$$

Where:

Y – modeled response;

$\bar{X}$ – average for the modeled response.

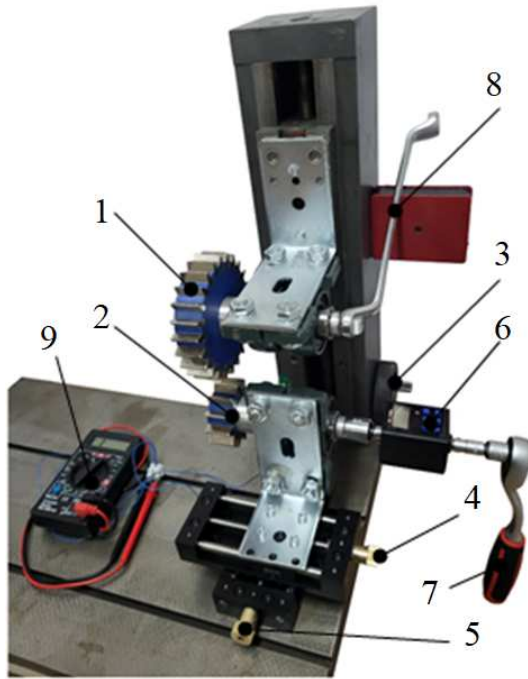


Fig. 6. The layout for conducting experiments.

3.4 Model verification. Degrees of freedom criterion

The model is verified [20] from the perspective of the criterion of the number of degrees of freedom. The way in which the degrees of freedom of the model were determined is explicit in Table 3.

Table 3

Determining the degrees of freedom of the model.

Y	=	X	+	A	+	B
Nr. of levels				3		3
Degrees of freedom (DF)		1		2		2
DF=1+2+2=5						

From the perspective of the model that has 5 degrees of freedom, the orthogonal table used for the experiment should have a minimum of 5 lines (experiments).

3.5 Model verification. Orthogonality criterion

To verify orthogonality, the method presented by [20] is applied, consisting in determining the least common multiple, using a double-entry Table 4.

Table 4

Model verification. Orthogonality criterion.

Factors and Levels for Factors	3	A [mm]	*	
	3	B [mm]	3 ²	*
		A [mm]	B [mm]	
		3	3	
Factors and Levels for Factors				

To construct Table 4, the following procedure was followed:

- Each factor was placed on rows and columns with the number of levels broken down into prime numbers;
- (*) was placed at each intersection of non-disjoint actions;
- The product of the number of levels at each intersection between two disjoint actions was made.

It can be seen that the least common multiple is 9; therefore, the orthogonal plane that can be used must have a minimum of 9 lines (experiments).

3.6 Establishing the test plan

Given that the factors in the experiment are at three levels, and the minimum number of lines should be nn, the orientation is towards an L₉ matrix (orthogonal arrays) with the factors at 3 levels.

The orthogonal arrays was identified in Table 5, a orthogonal arrays with 9 experiments [21].

Table 5

Orthogonal Arrays L₉(3⁴).

	1	2	3	4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1

6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The Orthogonal Arrays $L_9(3^4)$ has the associated linear graph presented in Figure 7.

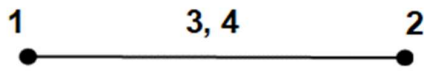


Fig. 7. Linear graph for orthogonal arrays $L_9(3^4)$.

3.7 Calculation of theoretical response and errors (residuals)

The model has the form:

$$Y \cong \bar{X} + A + B \quad (2)$$

And the average effect of the factors being calculated, the theoretical answer can be determined, as follows:

$$Y_t \cong \bar{X} + \begin{bmatrix} 3.43 \\ -1.27 \\ -2.17 \end{bmatrix} * A + \begin{bmatrix} -1.73 \\ -0.30 \\ 2.03 \end{bmatrix} * B \quad (3)$$

The error (residual) will be calculated with the formula:

$$Error = Y - Y_t \quad (4)$$

Where:

Y : measured response;

Y_t : theoretical answer.

The theoretical response is predicted using factor effects at optimal levels. The data are presented in Table 6.

3.8 Calculation of the average effect of factors

The general calculation formula for the average effect of factors is:

$$E_{Fi} = M_{Fi} - \bar{X} \quad (5)$$

Where:

E_{Fi} - the effect of the factor at level i ;

M_{Fi} - the average of the response when the factor F is at level i ;

$\bar{X}$ - the overall average for the measured response.

The average effect of the factors for each response is presented in Table 7.

Table 6

Responses to the experience plan.					
Experiments	Factor A	Factor B	Measured response $\bar{Y}$ [kgf*cm]	Theoretical response $\hat{Y}$ [kgf*cm]	Residu d
1	1	1	7.1	8.47	-1.37
2	1	2	9.5	9.90	-0.40
3	1	3	14	12.23	1.77
4	2	1	4.1	3.77	0.33
5	2	2	5.5	5.20	0.30
6	2	3	6.9	7.53	-0.63
7	3	1	3.9	2.87	1.03
8	3	2	4.4	4.30	0.10
9	3	3	5.5	6.63	-1.13
Overall average value of responses			6.77	6.77	

Table 7

Means effect of factors on responses.		
The average effect of factors on the Torque response		
Factor A		
Factor levels A [mm]	Average effect of factor A	Average value - Average effect of factor A
25	10.2	3.43
12.5	5.5	-1.27
8.3	4.6	-2.17
Factor B		
Factor levels B [mm]	Average effect of factor B	Average value - Average effect of factor B

88	5	-1.73
84	6.5	-0.30
82	8.8	2.03

4. RESULTS

The graphical representation of the average effects of the factors on the responses is presented in Figures 8 and 9.

These graphs allow us to visualize the importance of each factor and how it influences the evolution of the process.

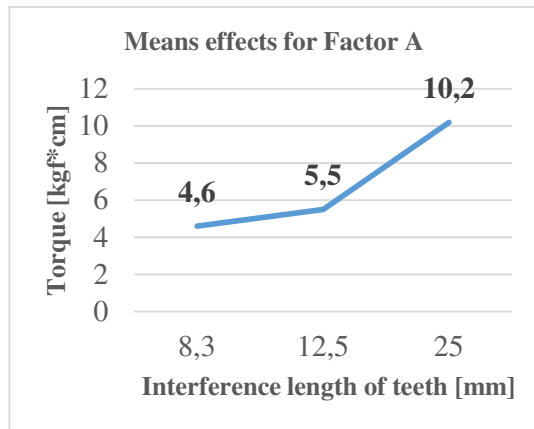


Fig. 8. Means effect for Factor A.

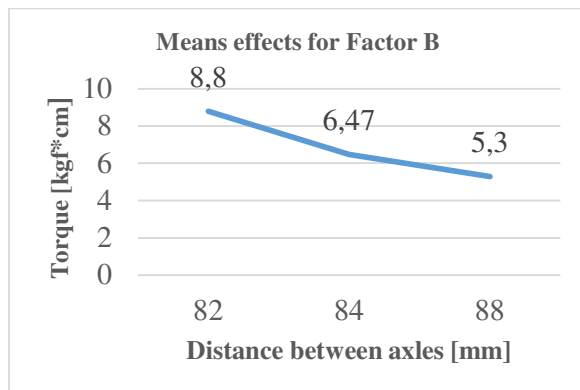


Fig. 9. Means effects for Factor B.

Table 8 presents the Analysis of Variance for Means, where:

DF: Degrees of Freedom;
Seq SS: Sequential Sum of Squares;
Adj SS: Adjusted Sum of Squares;
Adj MS: Adjusted Mean Squares
F: F-value;
P: P-value.

Analysis of Variance (ANOVA) is a statistical method used to compare the means of multiple groups to determine whether there are significant differences between them. It assesses whether the observed variations in the data arise due to actual differences between groups or due to random chance.

Table 8

Analysis of Variance for Means.						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	54.260	54.260	27.130	13.38	0.017
B	2	21.687	21.687	10.843	5.35	0.074
Residual Error	4	8.113	8.113	2.028		
Total	8	84.060				

5. DISCUSSIONS

Figure 8, main effects plot for Factor A, showing how the response variable ("Torque" in kgf*cm) changes with different levels of Interference Length of Teeth (mm). Concerning trend interpretation, torque increases as interference length increases from 8.3 mm to 25 mm. The highest torque value (10.2 kgf*cm) is observed at 25 mm interference length. The torque increase suggests that more engagement of teeth improves force transmission.

Figure 9 presents the main effects plot for Factor B, showing how torque (kgf*cm) varies with the distance between axes (mm). As the distance between axes increases, torque decreases. The system performs best at 82 mm in terms of torque output. It should be noted that, in essence, the distance between the axes determines the width of the contact between the teeth.

Table 8 presents the Analysis of Variance for Means.

The Sequential Sum of Squares (Seq SS) in ANOVA measures the variance explained by each factor in the order it is added to the model. It provides insight into how much additional variation in the dependent variable is explained by including a particular factor after accounting for those already in the model. The Seq SS depends on the order in which factors are entered into the model.

In the experiment presented, concerning Seq SS, Factor A explains 54.260 units of variation and Factor B explains 21.687 units.

The Adjusted Sum of Squares (Adj SS) in ANOVA measures the unique contribution of each factor independent of the order in which they are entered into the model. Unlike Sequential SS, which depends on the order of factor entry, Adjusted SS evaluates the variance explained by each factor after accounting for all other factors in the model. Adjusted Sum of Squares is not affected by the order in which factors are entered into the model.

In the experiment presented, concerning Adj SS, Factor A explains 54.260 units of variation and Factor B explains 21.687 units.

It can be observed that for both factors Seq SS=Adj SS. If Seq SS=Adj SS, the factor's contribution is independent of other factors. It means that the factor's contribution to the model does not depend on the order in which it was entered. This indicates a well-structured model where each factor has its own distinct effect.

The Adjusted Mean Squares (Adj MS) is a key metric in ANOVA, representing the variance attributed to a factor or the error term, scaled by its degrees of freedom (DF). It provides a normalized measure of the variability explained by each factor or the residuals, enabling meaningful comparisons between factors. A larger Adj MS compared to the error term suggests that the factor has a strong influence. Adjusted Mean Squares = Adj SS / DF. Factor A contributes the most variation per degree of freedom. Factor B contributes some variation but less than Factor A.

The F-value compares the variance explained by the factor to the residual error. Higher F-values indicate a greater likelihood that the factor has a significant effect. Factor A ($F = 13.38$) has a strong effect. Factor B ($F = 5.35$) has a moderate effect.

The p-value in Analysis of Variance measures statistical significance (probability of observing such results if the null hypothesis were true).

Using the threshold ($\alpha = 0.05$), If $p < 0.05$ the factor is statistically significant.

Factor A ($P = 0.017$) is significant at the 5% level and has a significant effect on response. Factor B ($P = 0.074$), is not significant at 5% level, but marginally significant at 10% level,

might have an effect, but it is not strongly significant.

6. CONCLUSIONS

The contact between two teeth, two gears, involves at least two factors: the width of the contact and the distance between the axes of the gears, which determines the height of the contact between the teeth. If we assign the width of the contact to Factor A, and the height of the contact to Factor B, we could study the process from a systemic perspective. The results revealed that Factor A has a strong effect and Factor B has a moderate effect.

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Studii privind proiectarea și performanța unui angrenaj planetar magnetic

Angrenajele magnetice sunt dispozitive inovatoare care emulează funcționalitatea angrenajelor mecanice tradiționale folosind câmpuri magnetice în loc de contactul fizic între dinți. Subiectul preocupărilor noastre este studiul performanțelor și elementelor de proiectare pentru un angrenaj magnetic planetar. Originalitatea angrenajului magnetic propus constă în faptul că dispunerea angrenajelor și forma geometrică a dinților permit, la limită, angrenarea mecanică. Problema care se pune este de a determina cât mai precis momentul capabil să fie transmis magnetic la nivelul dintre doi dinți și apoi prin extrapolare se poate determina cuplul capabil la nivelul angrenajului magnetic planetar.

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