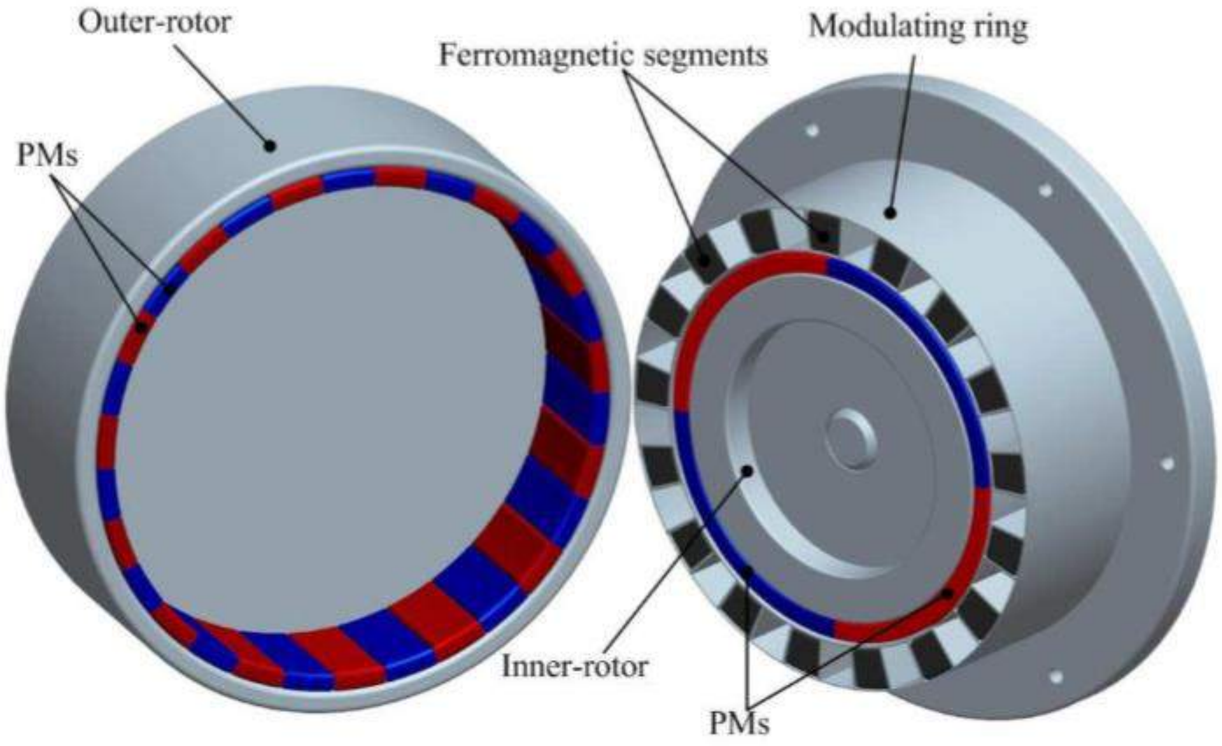


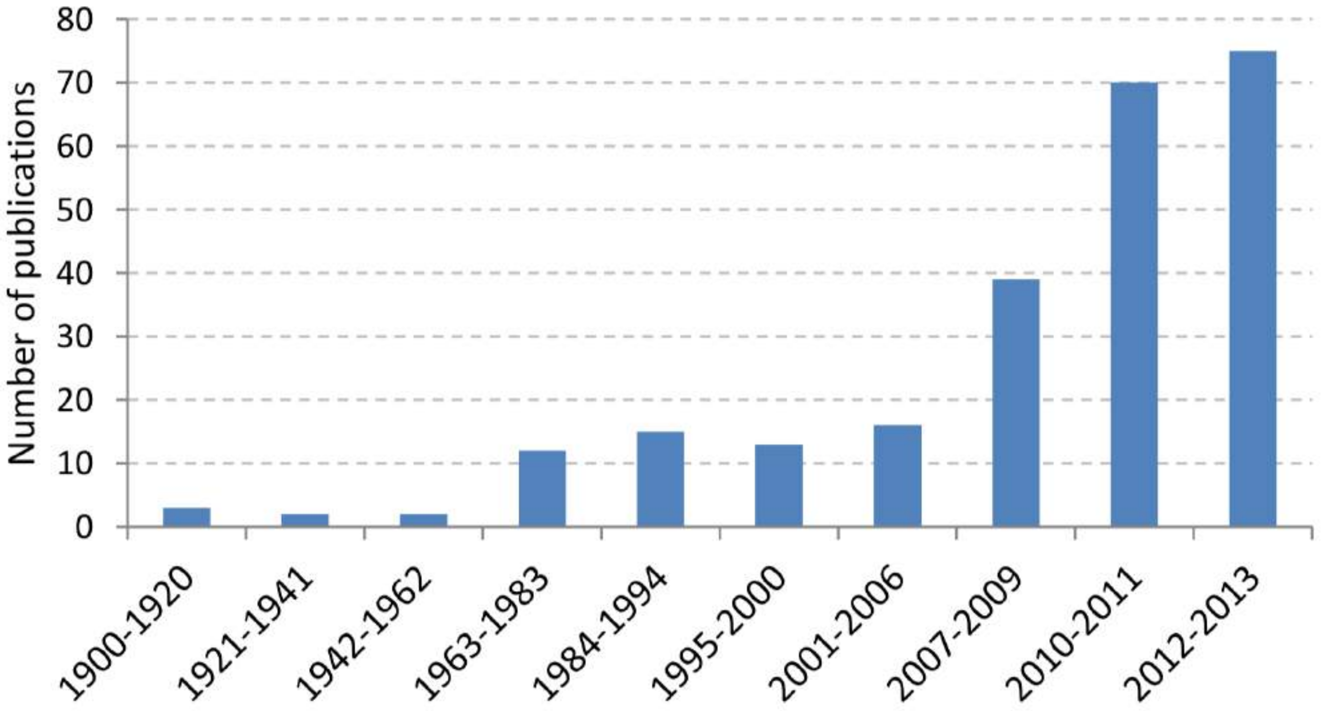
Coaxial Magnetic Gear (CMG)

Optimum design for improving modulating effect using response surface methodology and genetic algorithm

L. Jian, G. Xu, J. Song, H. Xue, D. Zhao, J. Liang

CONTEXTE : Why use CMG ?

Publication histogram on magnetic gears



Magnetic Gear Technologies: A Review, P.M. Tlali, R-J. Wang, S. Gerber

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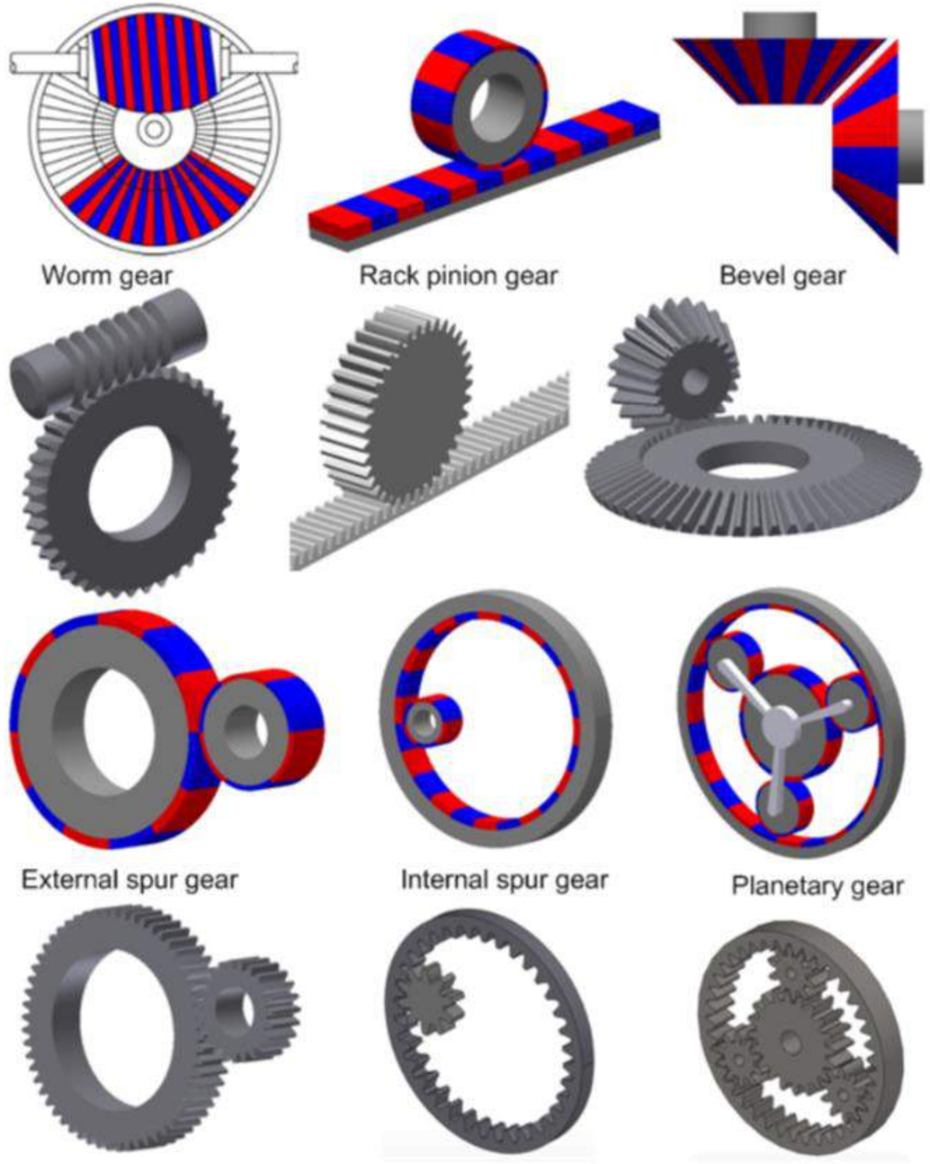
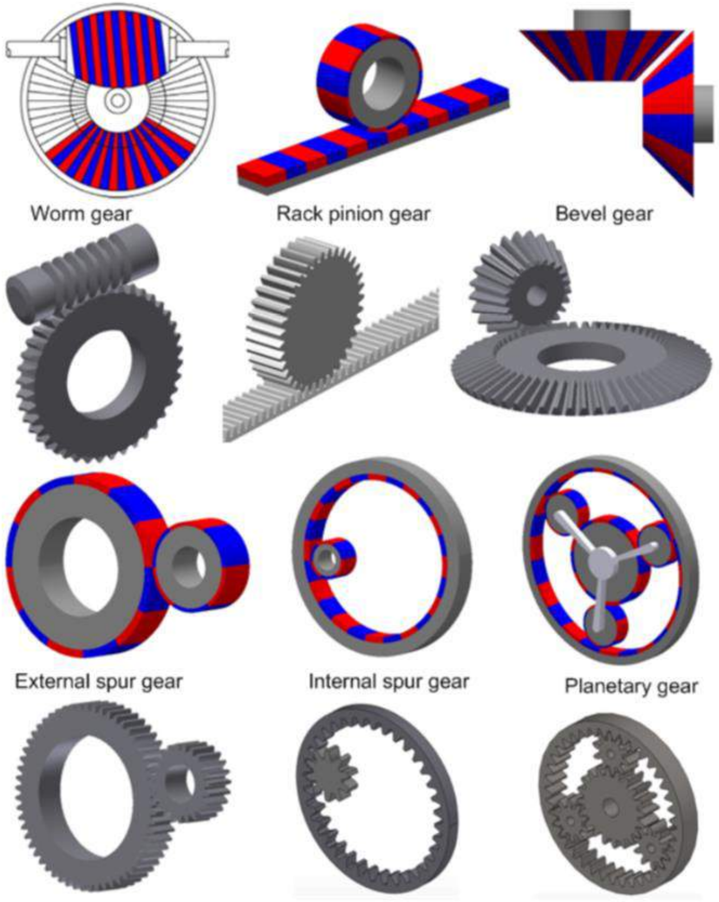
Comparison with mechanical gear



Picture from Magnetic Gear Technologies: A Review, P.M. Tlali, R-J. Wang, S. Gerber

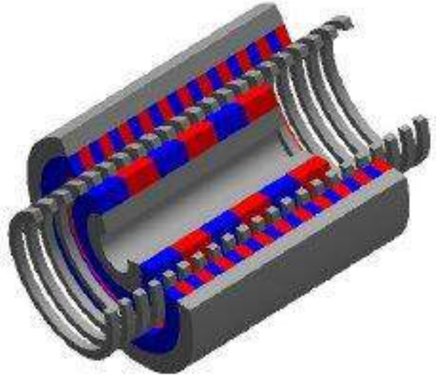
Two types of magnetic gears

Converted magnetic gears

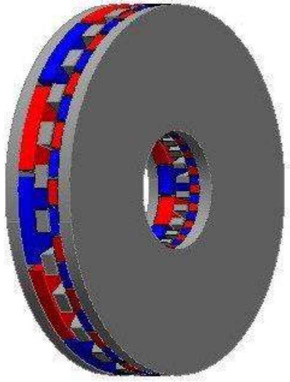


Pictures from Magnetic Gear Technologies: A Review, P.M. Tlali, R-J. Wang, S. Gerber

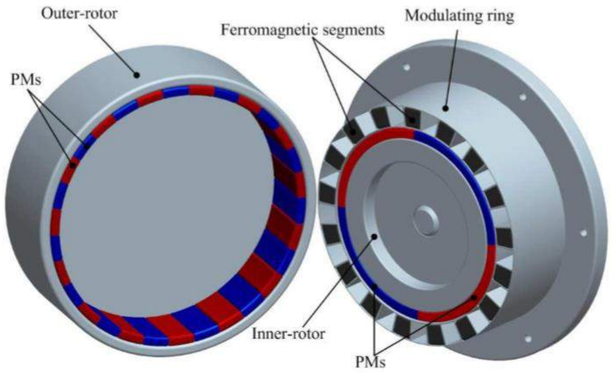
Field modulated magnetic gears



Linear type



Axial type



Coaxial type

Mechanical gear vs Magnetic gear

Advantages

- High torque density
- High efficiency: 99% of the power is transmitted to the load
- Easy to make

- Non-contact gear → physical isolation between shafts
- No wear
- No maintenance
- No friction
- Protective mechanism against overloading

Defaults

- Break if overloaded
- Need a good maintenance (lubrification)
- No isolation possible
- Noisy

- Harmonics create vibrations
- Fabrication process (mechanically, kinematically complicated to achieve)

Comparison with mechanical gear

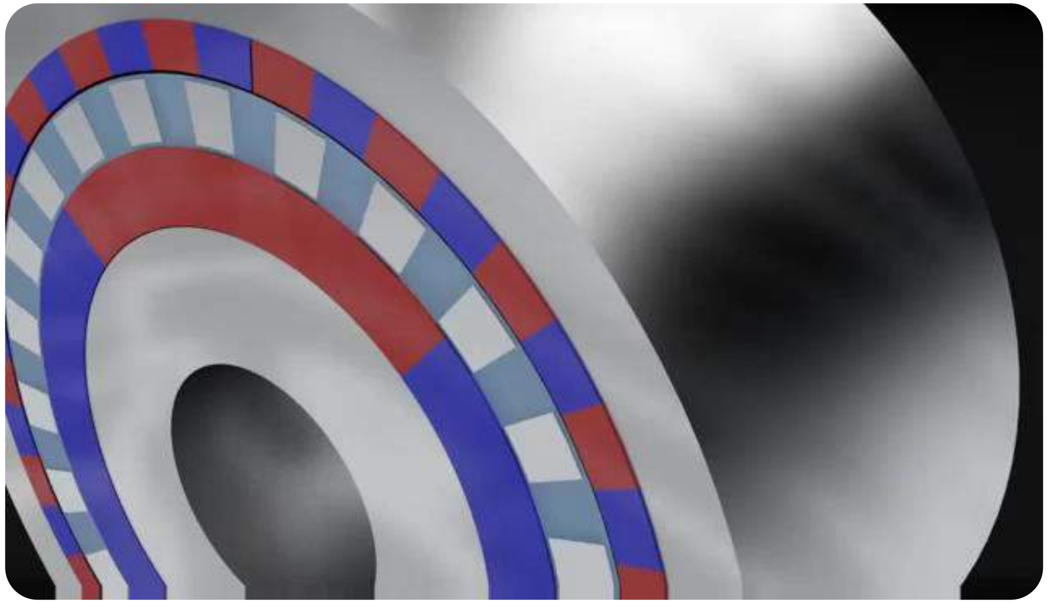
Why do magnetic gears exist ?

Definitively useful for :

- Safety requirements
  ⇒Can not break if overloaded

- Location difficult to reach
  ⇒Maintenance reduced

- Isolate the motor and the load
  ⇒Contact less transmission



CMG working principle

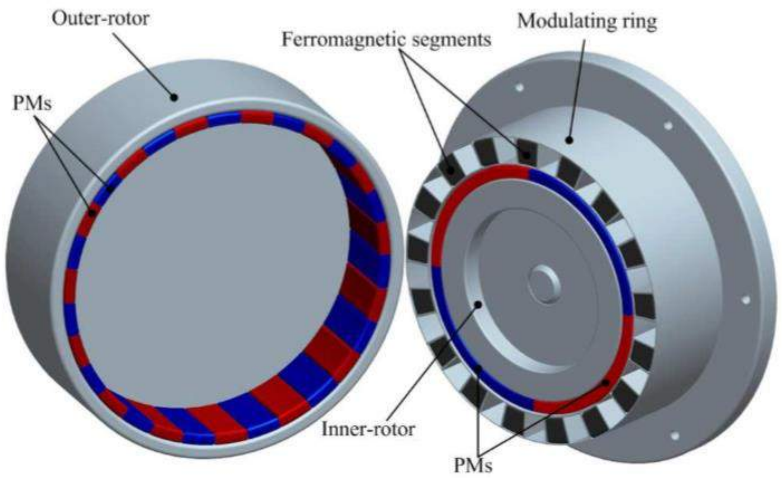
Goal:

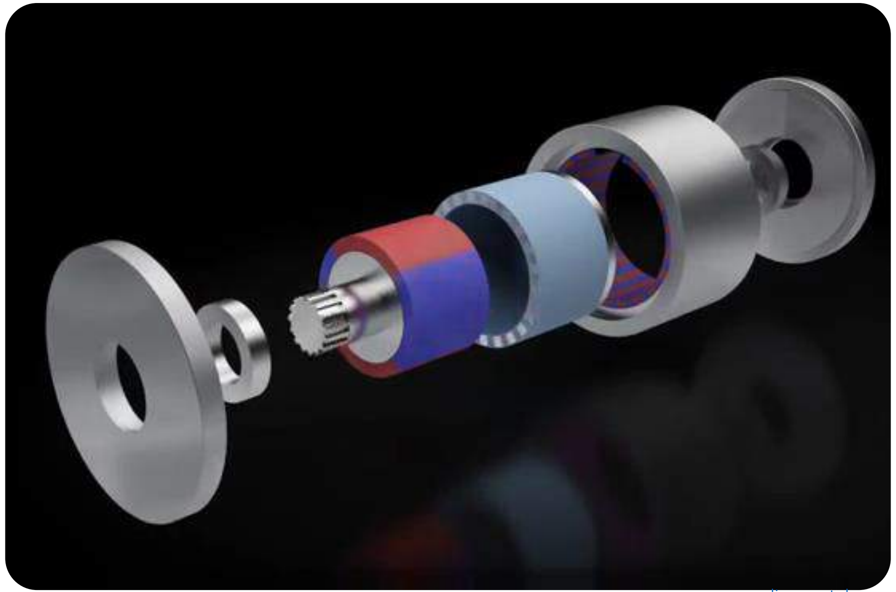
- Torque transmission and speed variation between two shafts (inner and outer) rotating at different speeds.
- No mechanical contact → interaction between **magnetic field** of permanent magnets.

Structure → Three gears:

- Two permanents magnets rings, with a different number of poles
- One ferromagnetic ring with gaps between ferromagnetic parts

↳ creates the **modulating effect**





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CMG working principle

Inner ring

- low number of magnets → connected to the high-speed shaft

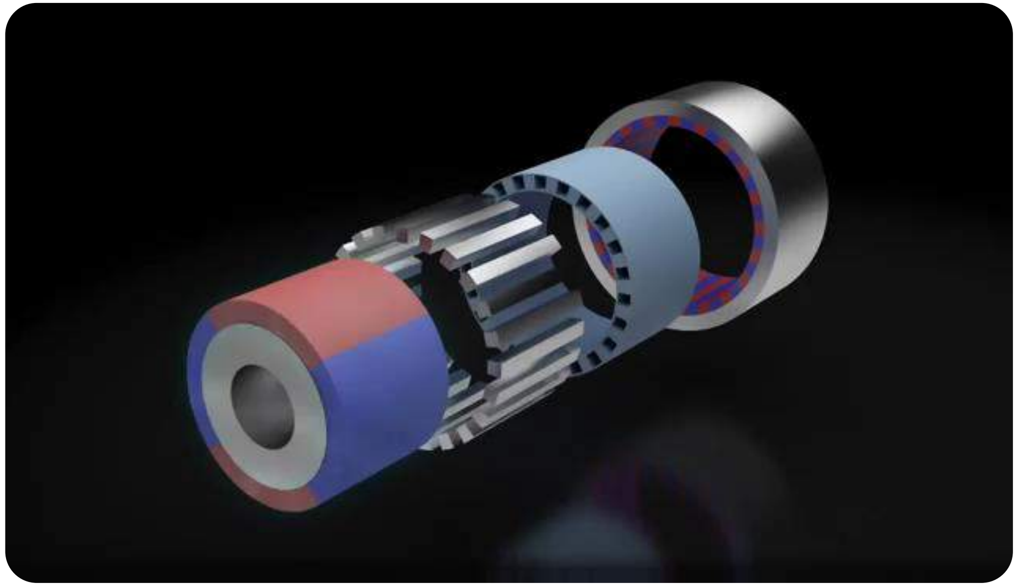
Middle ring = Modulating ring

- ferromagnetic segments held in a mechanical structure.

Outer ring

- High number of magnets → connected to the low-speed shaft

Two of them are rotating and the other is fixed. According to which one is fixed, we have a different gear ratio



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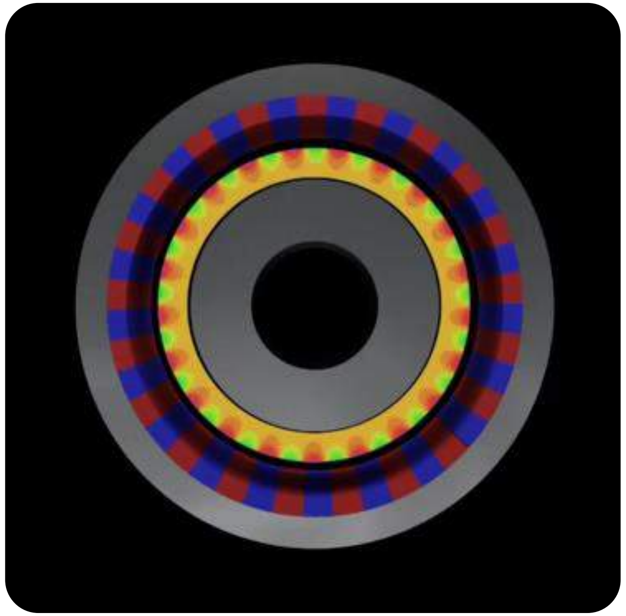
⚠ there is no physical contact between any of the rings!

CMG working principle

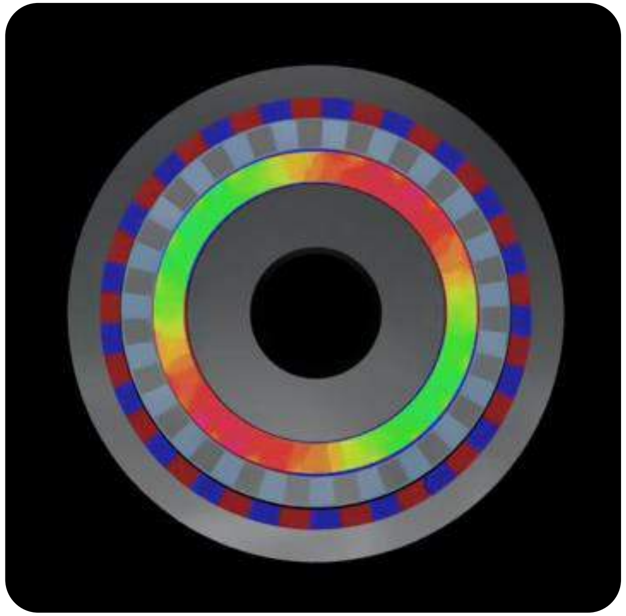
How does it work?

Field of the outer magnets:



Array of north/south poles rotating at low speed

Field of the outer ring after modulation by the ferromagnetic ring



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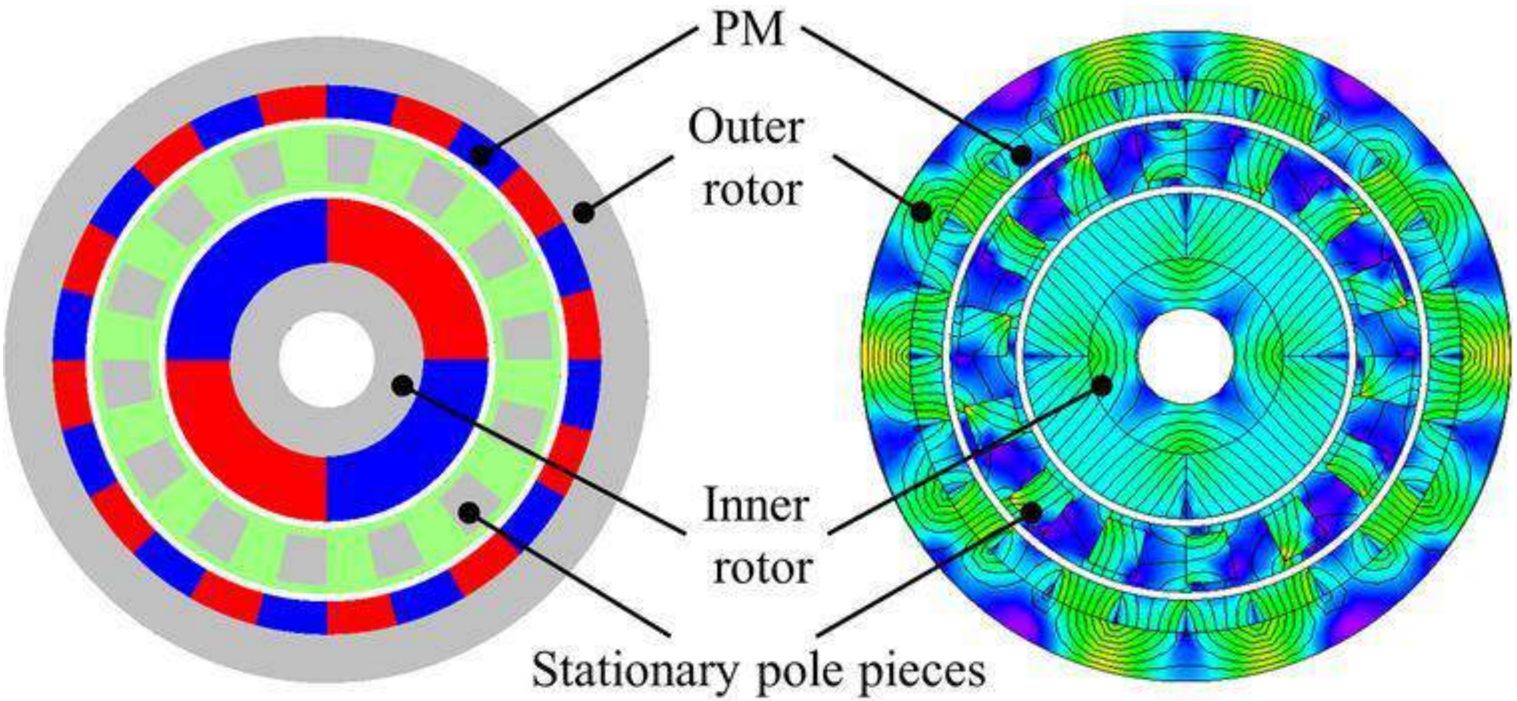
The ferromagnetic ring alters/modulates this field pattern. Resulting field has less poles rotating at a **higher** speed and in a **different direction**.

CMG working principle

How does it work?

Field of the outer magnets:

Field of the outer ring after modulation by the ferromagnetic ring



A inner ring consisting of two north and south poles will **couple** with this field and rotate at this higher speed

CMG 1-D analytical model

The **goal** is to determine the field modulated by the ferromagnetic rods to prove that some **harmonics have the same number of poles.** Therefore these pair of harmonics interact with each other to **produce a stable magnetic torque.** This **model** can then be use to optimize the parameters in order to **maximize the torque**.

Procedure :

1. **MMF** caused by the **PM.**
2. We can determine the **permeance of the magnetic circuit.**
3. The **resulting field** is given by the product of the MMF and the permeance.
4. The **torque** finally computed as a product of harmonics

CMG 1-D analytical model

Quick reminder

The **MMF** is the product of the flux and the reluctance

$$F = \Phi R = \int H\, dl$$

The inverse of the reluctance is the **permeance**

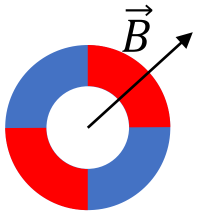
$$R = \frac{l}{\mu_0 S} = \frac{1}{P}$$

The **flux** is tje product of the magnetic field time dthe surface

$$\Phi = \iint B\, ds$$

Hypothesis

1. field B to be puerly radial



2. Ferromagnetic rods : $\mu = \infty$

The permeance from the air is negligible in comparison, thus all the flux line flows through the metal part.

3. Magnet : $\mu = \mu_0$

MMF : $F = \Phi R = \int H\, dl$

Permeance : $R = \frac{l}{\mu_0 S} = \frac{1}{P}$

Flux : $\Phi = \iint B\, ds$

CMG 1-D analytical model

In the paper

We introduce a surface permeance

$$R_s = \frac{l}{\mu_0} = \frac{1}{P_s}$$

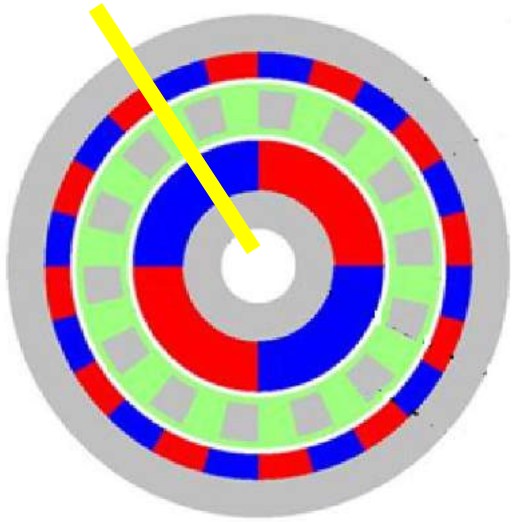
Starting form the MMF expression we obtain

$$\Phi(\theta) = F(\theta)\, P(\theta)$$
$$\iint B\, ds = F(\theta) \frac{\mu_0 S}{l}$$

Considering now that we have a **tube from infenitesimal section (in yellow)**, the integral can be replaced by a delta.

$$B(\theta)\, \Delta s = F(\theta) \frac{\mu_0 \Delta S}{l(\theta)}$$
$$B(\theta) = F(\theta)\, P_s(\theta)$$

$$ds = r\, d\theta \mathrm{dz}$$



In other words, we condisder the field to be constant inside each infinitesimal pipe. We discreatize the space.

CMG 1-D analytical model

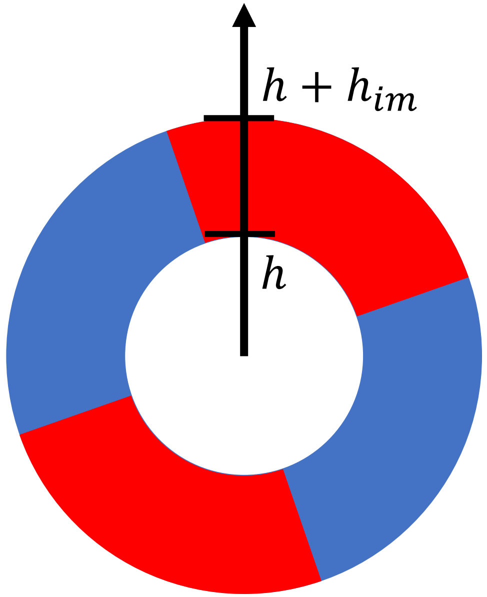
Procedure :

1. **MMF caused by the PM.**
2. We can determine the permeance of the magnetic circuit.
3. The resulting field is given by the product of the MMF and the permeance.
4. The torque finally computed as a product of harmonics

$$R_s = \frac{l}{\mu_0} = \frac{1}{P_s}$$

CMG 1-D analytical model

1. MMF generated by the PM’ s



Computing the MMF

$$\int_h^{h+h_{im}} H(\theta)\, dl = \frac{B(\theta) h_{im}}{\mu_0}$$

$$R_s(\theta) = P_s^{-1}(\theta) = \frac{h_{im}}{\mu_0}$$

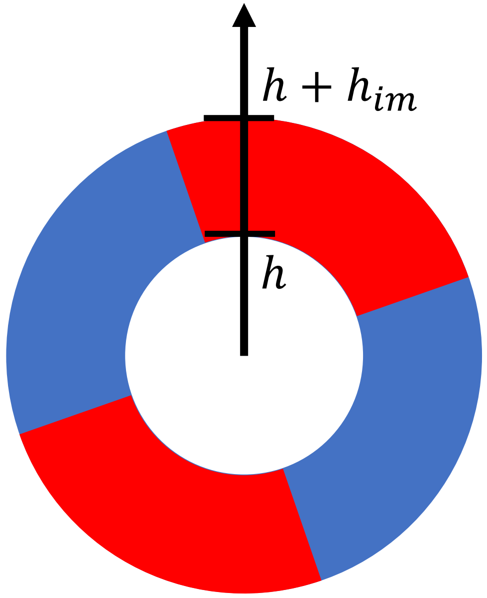
Flux is puerly radial, thus the dot procduct is null on the circular path.

Recalling that P_s link the MMF and $\vec{B}(\theta)$ we deduce :

$$F(\theta) = \frac{B(\theta)}{P_s(\theta)}$$

CMG 1-D analytical model

1. MMF generated by the PM’s



A sinusoïdal aimantation of the magnet is now consider.

$$F(\theta) = \frac{\boxed{B(\theta)} h_{im}}{\mu_0}$$

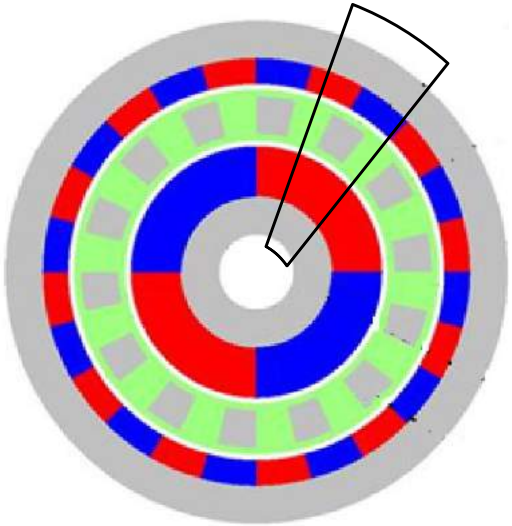
$$F_{magnet} = \frac{\boxed{B_{remanent}} h_{magnet}}{\mu_0} \boxed{\cos(p(\theta + \omega t + \alpha_0))}$$

CMG 1-D analytical model

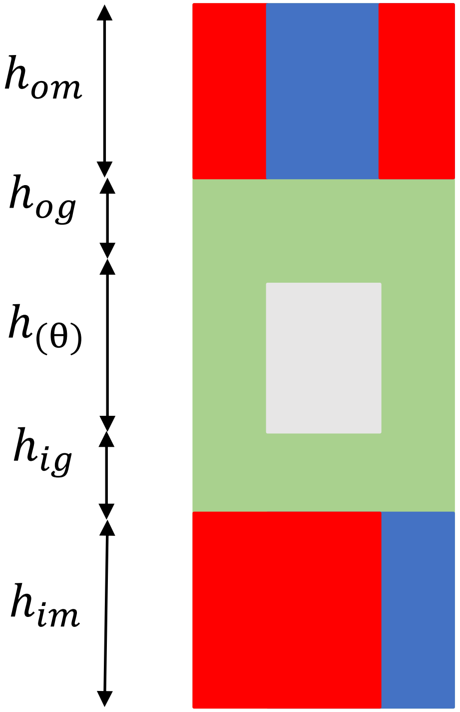
Procedure :

1. MMF caused by the PM.
2. **We can determine the permeance of the magnetic circuit.**
3. The resulting field is given by the product of the MMF and the permeance.
4. The torque finally computed as a product of harmonics

CMG 1-D analytical model



2. Permeance from the complet circuit

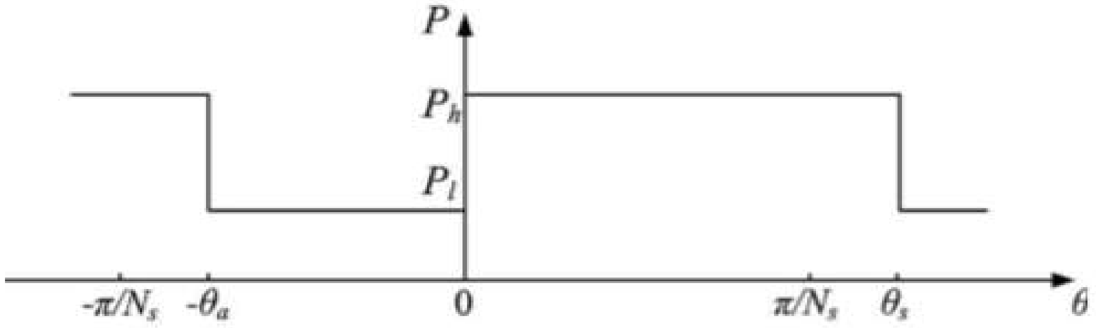


$$P_s(\theta) = \frac{1}{\rho_{im} + \rho_{ig} + \rho_{om} + \rho_{og} + \rho(\theta)}$$

$$\rho_i = \frac{h_i}{\mu_0}$$

$\rho_{(\theta)} = \frac{h(\theta)}{\mu_0}$ in front of a gap

$\rho_{(\theta)} = 0$ in front of a polar piece



CMG 1-D analytical model

2. Permeance from the complet circuit

It is another Fourrier's series

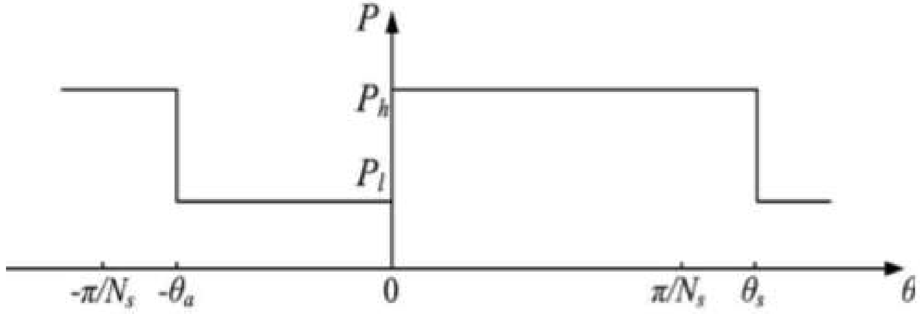
$$P(\theta) = P_0 + \sum_{j=1}^{+\infty} P_j \cos jN_s \left(\theta - \frac{\theta_s}{2}\right)$$

$$P_0 = \left(1 - \frac{N_s\theta_s}{2\pi}\right) P_l + \frac{N_s\theta_s}{2\pi} P_h$$

$$P_j = \frac{P_h - P_l}{j\pi} \sqrt{2(1 - \cos jN_s\theta_s)}$$

$$P_h = \frac{\mu_0}{h_{im} + h_{om} + h_{ig} + h_{og}}$$

$$P_l = \frac{\mu_0}{h_{im} + h_{om} + h_{ig} + h_{og} + h_s}$$



CMG 1-D analytical model

Procedure :

1. MMF caused by the PM.
2. We can determine the permeance of the magnetic circuit.
3. **The resulting field is given by the product of the MMF and the permeance.**
4. The torque finally computed as a product of harmonics

CMG 1-D analytical model

3. Harmonics expressions

$$B^{j}(\theta) = F(\theta)\ P_s^{\ j}(\theta)$$

$$F_{magnet} = \frac{B_{remanent}\ h_{magnet}}{\mu_0}\cos(\ p\ (\theta + \ t\ + \alpha_0))$$

$$P_s(\theta) = P_0 + \sum_{j=1}^{\infty} P_j \cos\left(j\ N_s\left(\theta\ - \frac{\theta_s}{2}\right)\right)$$

Replacing p by p_1/ p_2 , ω by ω_1 / ω_2 , $\cdots$ We get the fundamental and the first harmonics generated by each magnet.

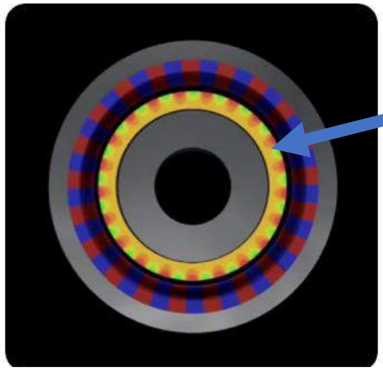
$$B^{0}(\theta) = \frac{B_{remanent}\ h_{magnet}\ P_0}{\mu_0}\cos(\ p\ (\theta + \omega\ t\ + \alpha_0))$$

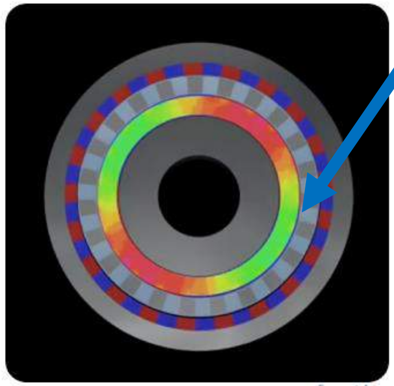
$$B^{1}(\theta) = \frac{B_{remanent}\ h_{magnet}\ P_1}{\mu_0}\cos(\ p\ (\theta + \omega\ t\ + \alpha_0))\cos\left(j\ N_s\left(\theta\ - \frac{\theta_s}{2}\right)\right)$$

CMG 1-D analytical model

3. Harmonics expressions

The idea was that harmonics could have the same number of pole and thus produce a stable torque





$$B^0_{om}(\theta) = \frac{B_{om}\, h_{om}\, P_0}{\mu_0} \cos(\, p_1\, (\theta + \omega_1\, t\ + \alpha_0))$$

$$B^1_{om}(\theta) = \frac{B_{om}\, h_{om}\, P_1}{\mu_0} \cos(\, p_1\, (\theta + \omega_1\, t\ + \alpha_0)) \cos\left(j\, N_s\, \left(\theta\ - \frac{\theta_s}{2}\right)\right)$$

$$B^0_{im}(\theta) = \frac{B_{im}\, h_{im}\, P_0}{\mu_0} \cos(\, p_2\, (\theta + \omega_2\, t\ + \beta_0))$$

$$B^1_{im}(\theta) = \frac{B_{im}\, h_{im}\, P_1}{\mu_0} \cos(\, p_2\, (\theta + \omega_2\, t\ + \beta_0)) \cos\left(j\, N_s\, \left(\theta\ - \frac{\theta_s}{2}\right)\right)$$

The only parameters we can change is N_s the number of magnetic rods.

CMG 1-D analytical model

3. Harmonics expressions

$$B_{\mathrm{om}}^{1}(\theta) = \frac{B_{om}\, h_{om}\, P_1}{\mu_0} \cos(\, p_1\,(\theta + \omega_1\, t\ + \alpha_0)) \cos\left(j\, N_s\, \left(\theta\ - \frac{\theta_s}{2}\right)\right)$$

$$\cos(A)\cos(B) = 0.5\cos(A+B)\cos(A-B)$$

Identification

Minimize

$$B_{\mathrm{om}}^{1}(\theta) = \frac{B_{om}\, h_{om}\, P_1}{\mu_0} \left\{ \boxed{\cos\left(N_s\, \left(\theta\ - \frac{\theta_s}{2}\right) -\ p_1\,(\theta + \omega_1\, t\ + \alpha_0)\right)} + \boxed{\cos\left(N_s\, \left(\theta\ - \frac{\theta_s}{2}\right) +\ p_1\,(\theta + \omega_1\, t\ + \alpha_0)\right)} \right\}$$

$$B_{im}^{0}(\theta) = \frac{B_{im}\, h_{im}\, P_0}{\mu_0} \boxed{\cos(\, p_2\,(\theta + \omega_2\, t\ + \beta_0))}$$

CMG 1-D analytical model

3. Harmonics expressions

$$\cos\left(N_s\theta - \frac{N_s\,\theta_s}{2} - p_1\theta - p_1\omega_1\,t - p_1\,\alpha_0\right) \qquad \cos(\,p_2\theta + \omega_2\,p_2\,t\, + p_2\beta_0)$$

First condition to have the **same variation in terms of theta**, we imposed that the number of poles are equals

$$p_2\theta = (N_s - p_1)\theta \qquad N_s = p_1 + p_2$$

Second condition to have the **same variation in terms of time**, we imposed the produc of speed and number of paire the pole to be equals

$$\omega_2\,p_2\,t = -p_1\omega_1\,t \qquad \frac{p_1}{p_2} = \frac{-\omega_2}{\omega_1} = G_r$$

CMG 1-D analytical model

3. Harmonics expressions

Basic rules to follow

p_1 = number of pairs of pole in the inner ring

p_2 = number of pairs of pole in the inner ring

N_S = number of ferro magnetic rods

G_r = reduction ratio

Rules give to optmize the harmonic content :

$$N_S = p_1 + p_2$$

$$G_r = \frac{p_1}{p_2}$$

CMG 1-D analytical model

3. Harmonics expressions

First linkage

$$B^0_{om} = \frac{P_0 B_{or} h_{om} \cos \boxed{p_1}(\theta + \boxed{\omega_1 t} + \alpha_0)}{\mu_0}$$

$$B^1_{im} = \frac{P_1 B_{ir} h_{im} \cos \boxed{p_1}\left(\theta - \boxed{\frac{1}{G_r}\omega_2 t} + \frac{\beta_0}{p_1} + \frac{\theta_s}{2p_1}\right)}{\mu_0}$$

Second linkage

$$B^0_{im} = \frac{P_0 B_{ir} h_{im} \cos \boxed{p_2}(\theta + \boxed{\omega_2 t} + \beta_0)}{\mu_0}$$

$$B^1_{om} = \frac{P_1 B_{or} h_{om} \cos \boxed{p_2}\left(\theta - \boxed{G_r \omega_1 t} + \frac{\alpha_0}{p_2} + \frac{\theta_s}{2p_2}\right)}{\mu_0}$$

By develloping the full expression of the magnetic field shows that harmonics can have the **same number of pole and the same speed.** The relation is also **bilateral.**

CMG 1-D analytical model

Procedure :

1. MMF caused by the PM.
2. We can determine the permeance of the magnetic circuit.
3. The resulting field is given by the product of the MMF and the permeance.
4. **The torque finally computed as a product of harmonics**

CMG 1-D analytical model

4. Torque

Be carefull if you are reading the paper.

$$\cancel{T_{\max} = \frac{P_0 P_1 B_{or} B_{ir} h_{om} h_{im} L}{\mu_0^2}}$$

The proper way to determine the torque is to start with co-energy stored

$$T = \frac{\partial W'}{\partial \theta_c}$$

θ_c is the angular position of the component on wich the torque is caluclated

$$W' = \frac{1}{2\mu_0} \int_V B^2 \mathrm{dV}$$

The co-energy can be computed with this equation. B is the radial component of the flux densisty.

CMG 1-D analytical model

4. Torque

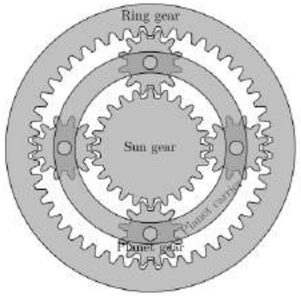
$$T_s = -\frac{p_s L M_s M_r \mathcal{P}^l_{avg} \mathcal{P}^l_{mod}}{8\mu_0 \pi^2}\left(\ln \frac{r_{mi} r_{rmo}}{r_{smi} r_{mo}}\right) \sin(p_s\theta_s + p_r\theta_r - Q_m\theta_m)$$

$$T_r = -\frac{p_r L M_s M_r \mathcal{P}^l_{avg} \mathcal{P}^l_{mod}}{8\mu_0 \pi^2}\left(\ln \frac{r_{mi} r_{rmo}}{r_{smi} r_{mo}}\right) \sin(p_s\theta_s + p_r\theta_r - Q_m\theta_m)$$

$$T_m = \frac{Q_m L M_s M_r \mathcal{P}^l_{avg} \mathcal{P}^l_{mod}}{8\mu_0 \pi^2}\left(\ln \frac{r_{mi} r_{rmo}}{r_{smi} r_{mo}}\right) \sin(p_s\theta_s + p_r\theta_r - Q_m\theta_m)$$

Number of poles
Shape factors
Material propreties
Load angle

Notation
S : sun
R : ring
M : modulator



$$T_m = \frac{-Q_m}{p_s} T_s = \boxed{-G_{sm}} T_s$$

$$T_r = \frac{p_r}{p_s} T_s = \boxed{G_{sr}} T_s$$

CMG 1-D analytical model : Synthesis

So far ?

- **Harmonics are the basic working principle**
  - **Same number of poles**
  - **Same angular speed**
- **Possible to thune the speed ratio by ajusting the numbers of pair of poles and the number of ferromagnetic segment**
- **Produce a stable magnetic torque.**

Next

- **Look at some results of the harmonics contends**
- **Algorithm to maximize the torque**

Analysis of the harmonics

View from the outer air gap :

Assumptions : ph=4 / pl=22 / ns=26

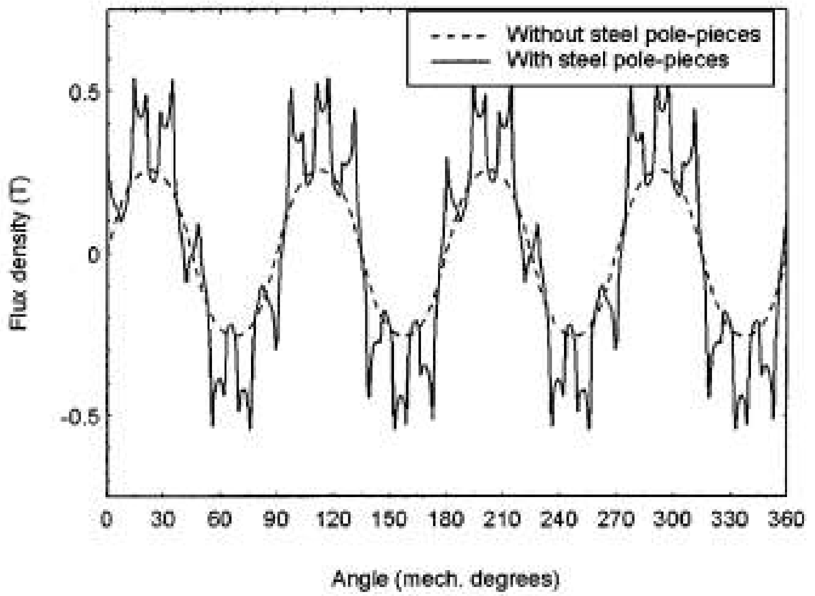


Fig. 2. Variation of radial flux density, due to high speed permanent magnet rotor, in airgap adjacent to low speed rotor.

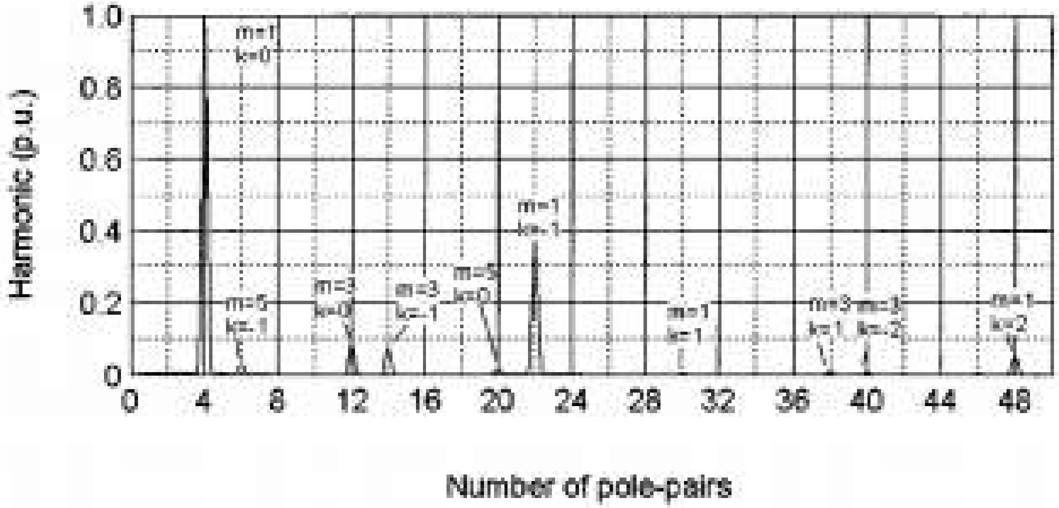


Fig. 3. Space harmonic spectrum of radial flux density, due to the high speed permanent magnet rotor, in airgap adjacent to low speed rotor.

Note :

- Rotational flux density space harmonis :
  $\Omega(m,k) = \frac{m*p}{m*p+k*ns} * \Omega r$ (if the stationnary ring speed null)
- Harmonic (m=1, k=-1) interact with the 22 pole-pair
- Gear ratio : $Gr= \frac{ph}{ph-ns} = \frac{-1}{5.5}$

Analysis of the harmonics

View from the inner air gap :

Assumptions : ph=4 / pl=22 / ns=26

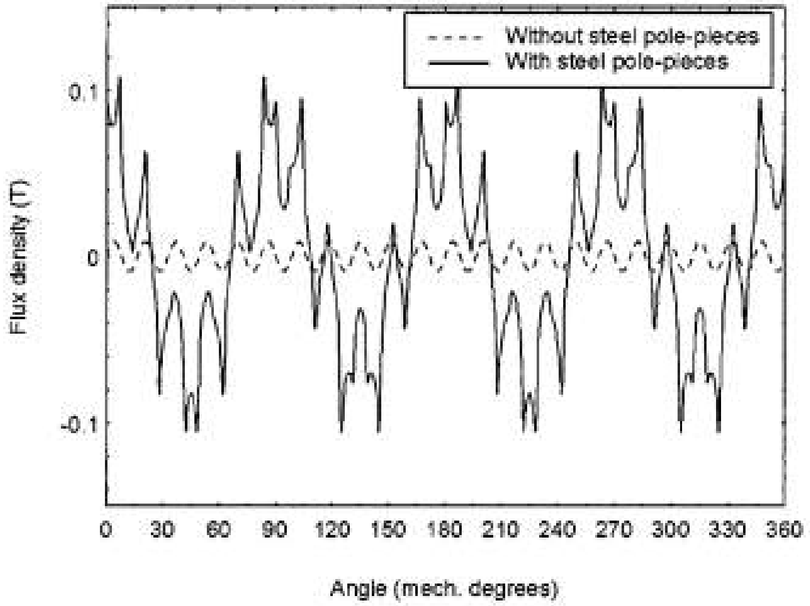


Fig. 4. Variation of radial flux density, due to low speed permanent magnet rotor, in airgap adjacent to high speed rotor.

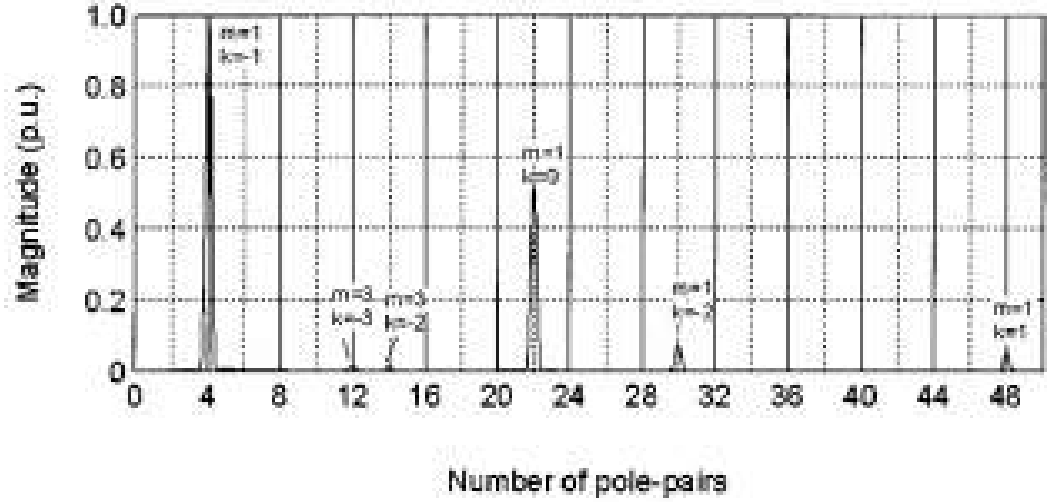


Fig. 5. Space harmonic spectrum of radial flux density, due to low speed permanent magnet rotor, in airgap adjacent to high speed rotor.

Note :

- Harmonic (m=1, k=-1) interact with the 4 pole-pair
- Gear ratio : Gr= $\frac{pl}{pl-ns}$ = -5.5

Impact of the modulating rotor

Assumptions : ph=4 / pl=10 / ns=14

<u>Without ferromagnetic pieces:</u>

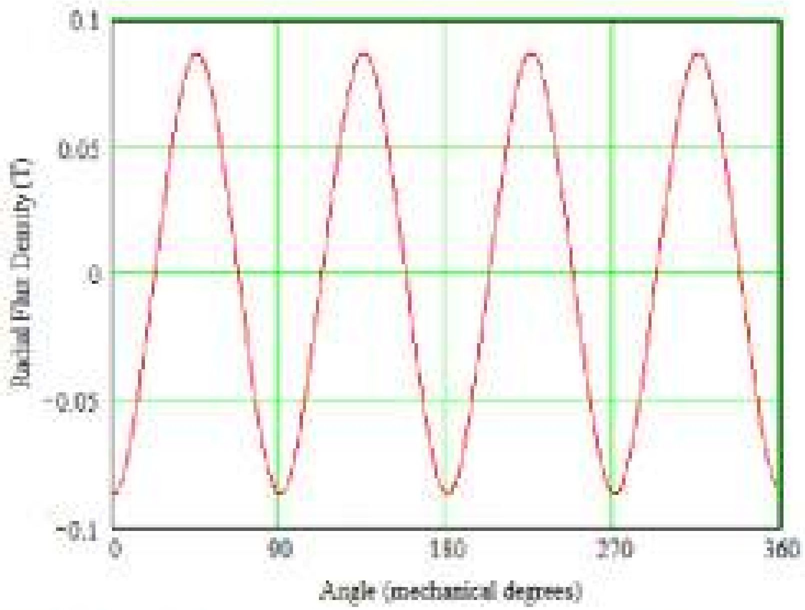


Figure 2. Radial field density at outer air-gap due to the inner magnets only, without modulating rotor.

<u>With ferromagnetic pieces:</u>

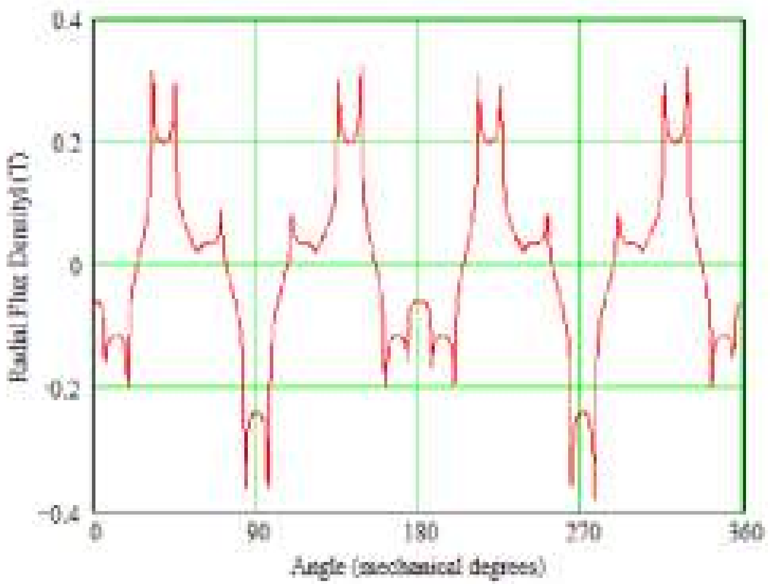


Figure 4. Radial field density at outer air-gap due to the inner magnets only, with modulating rotor.

Impact of the modulating rotor

Assumptions : ph=4 / pl=10 / ns=14

Without ferromagnetic pieces:

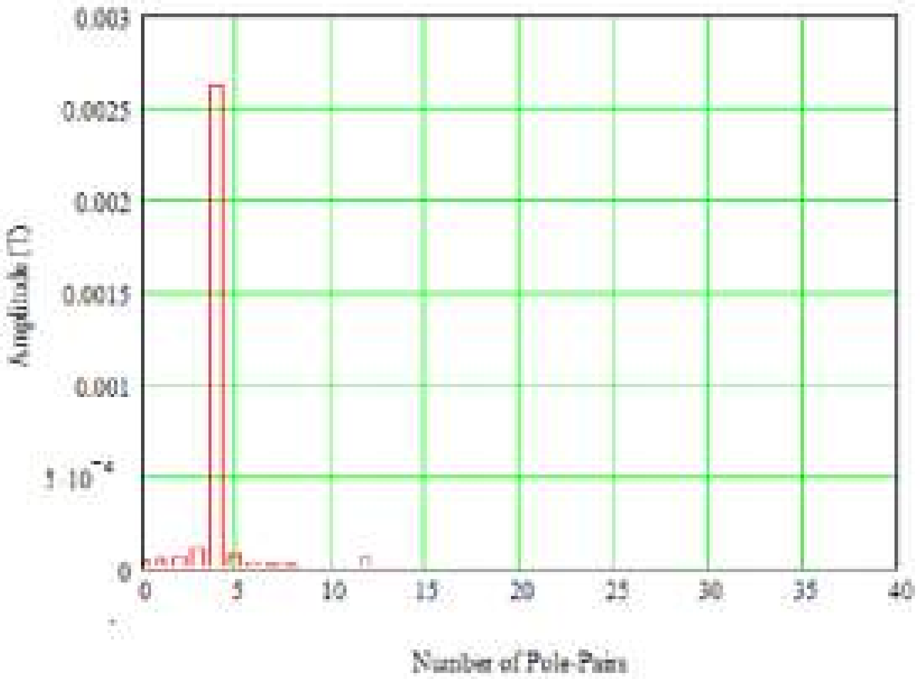


Figure 3. Radial field density harmonic content at outer air-gap due to the inner magnets only, without modulating rotor.

With ferromagnetic pieces:

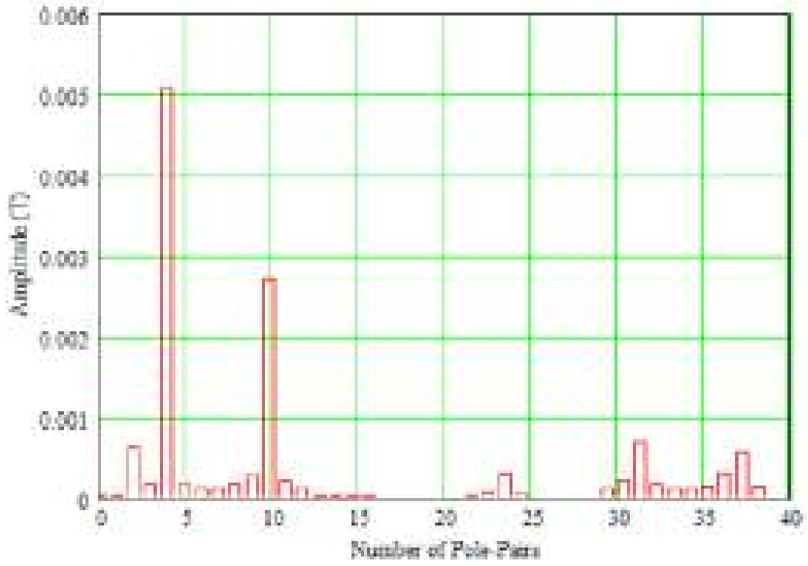


Figure 5. Radial field density harmonic content at outer air-gap due to the inner magnets only, with modulating rotor.

The asynchronous harmonic for p=10 produced by the inner rotor will interact with the fundamental one of the outer rotor and will produce efficient torque.

Impact of the modulating rotor

Complete = inner + outer rotor +ferromagnetic pieces

<u>Model complete of the CMG:</u>

In the outer air gap :

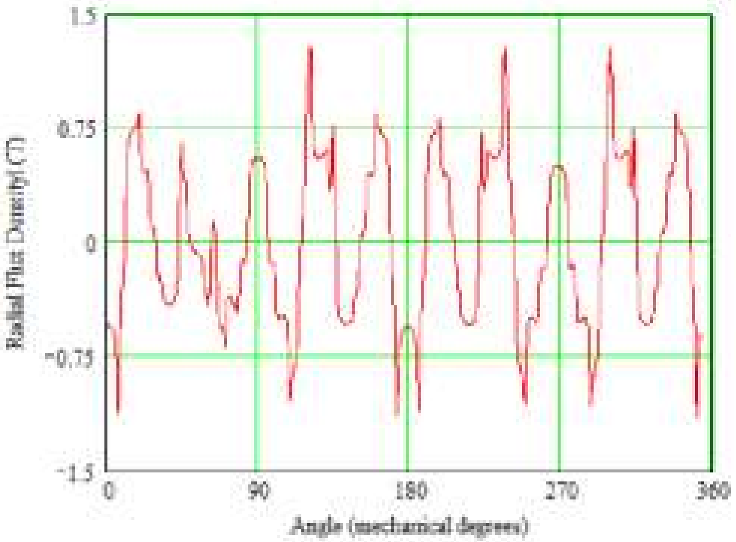


Figure 10. Radial field density at outer air-gap with CMG complete.

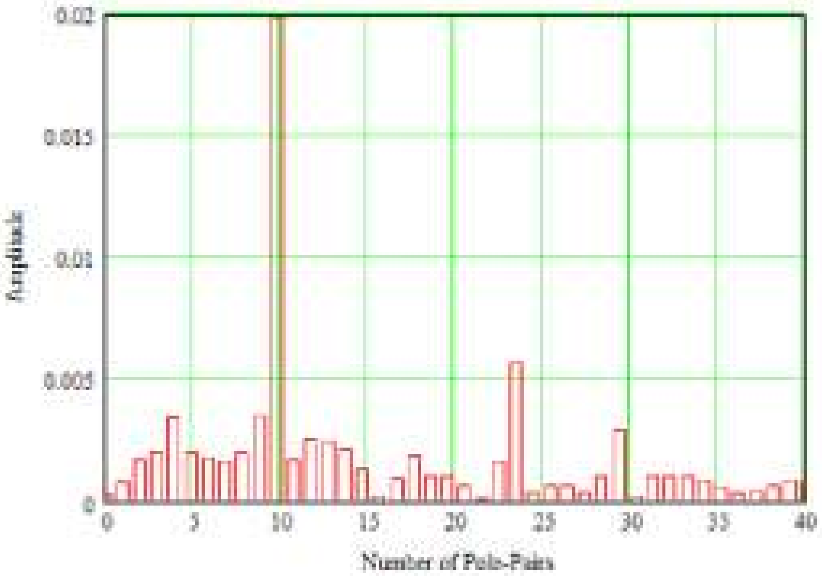


Figure 11. Radial field density harmonic content at outer air-gap with CMG complete.

<u>Note :</u>

- Greater mean value of the flux density in the outer air gap
- High content harmonic for p=4 & p =10

Impact of the modulating rotor

<u>Model complete of the CMG:</u>

Complete = inner + outer rotor +ferromagnetic pieces

<u>In the Inner air gap :</u>

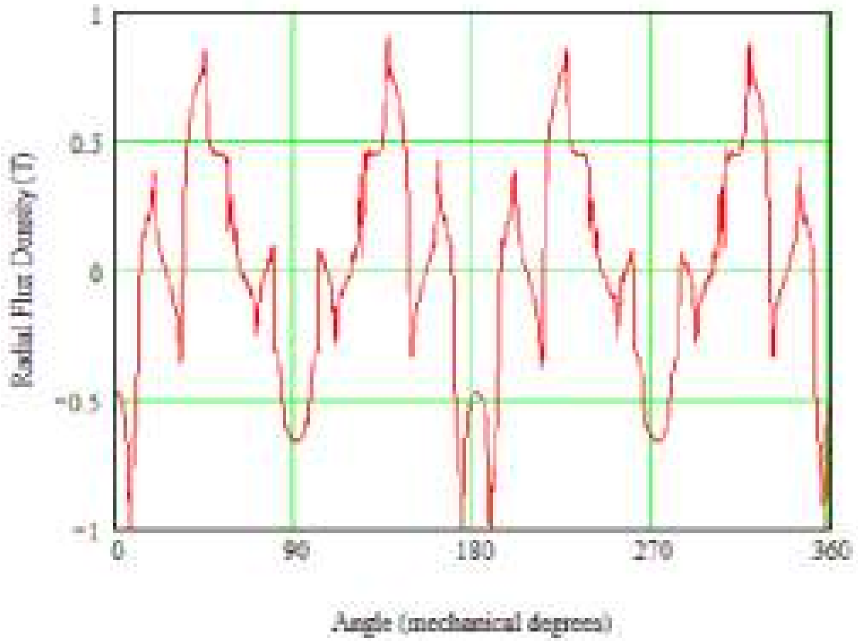


Figure 6. Radial field density at inner air-gap with CMG complete.

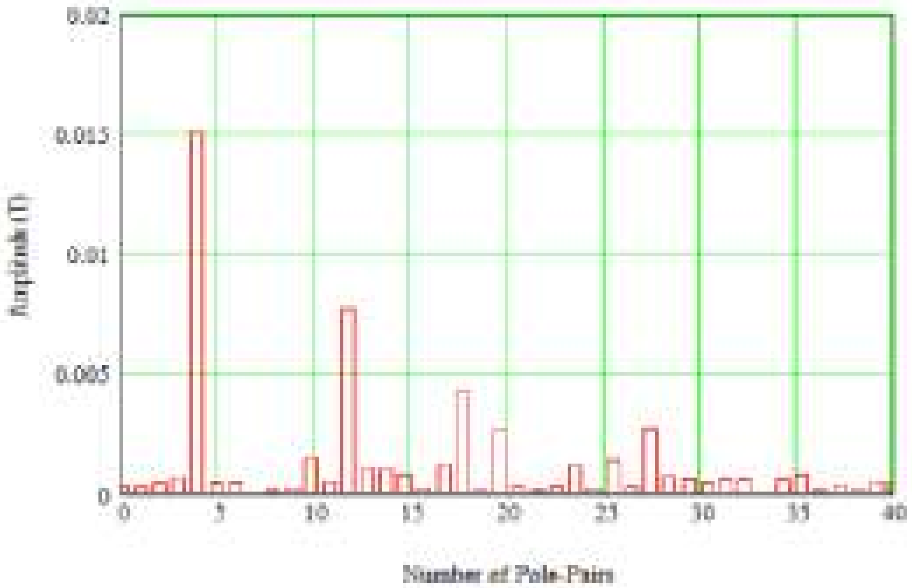


Figure 7. Radial field density harmonic content at inner air-gap with CMG complete.

Impact of the modulating rotor

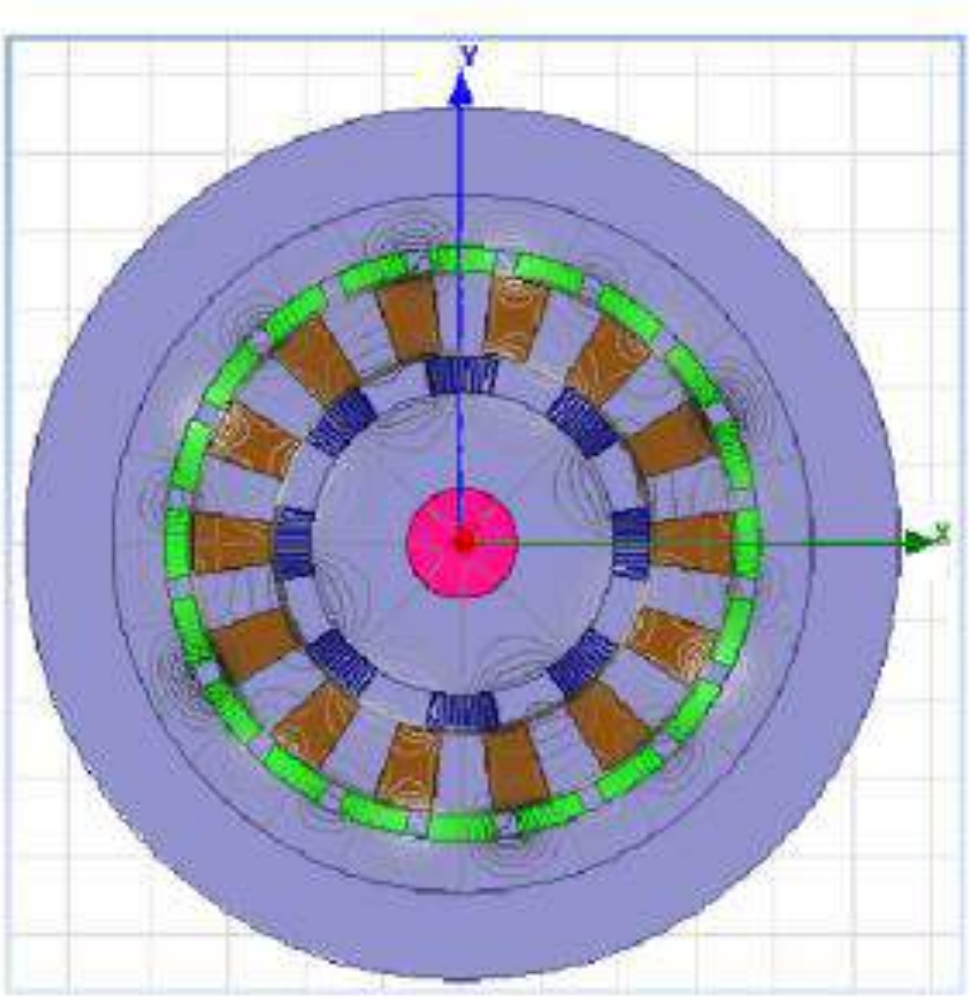


Figure 14. Flux line distribution in the CMG.

Note:

- large part of fluxlines can pass through the two air gaps
- part of flux lines contributes to the torque transmission.
- flux leakages between adjacent pole do not contribute for transmitting torque or power, and generate losses.

Cogging torque:

- Comes from the interaction of the rotor PMs with the steel pole-pieces
- Decreases the performance of CMG

<u>Torque on the inner rotor</u>

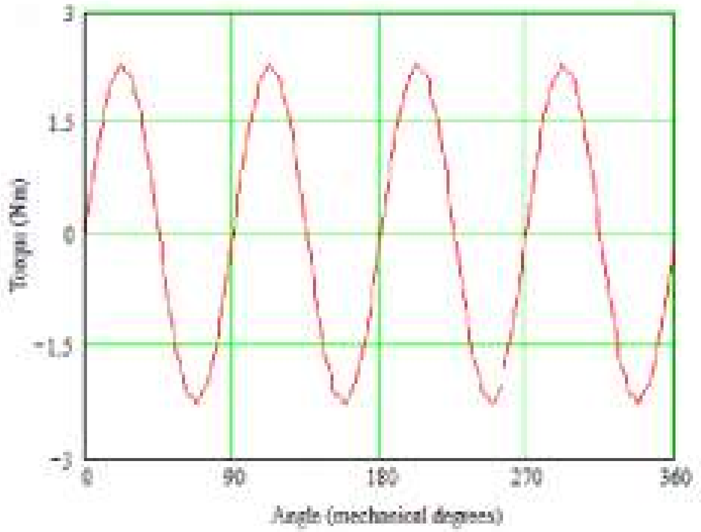


Figure 15. Magnetic torque on inner gap througout a complete revolution.

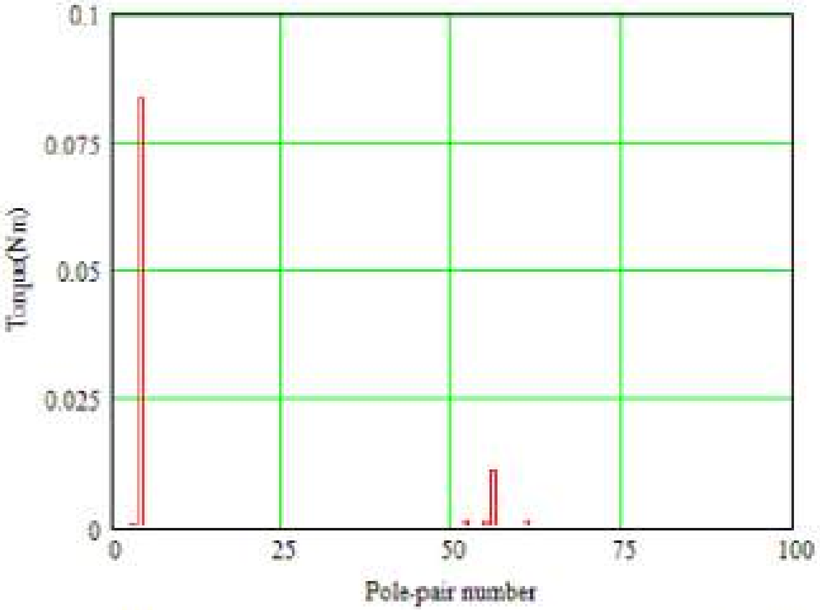
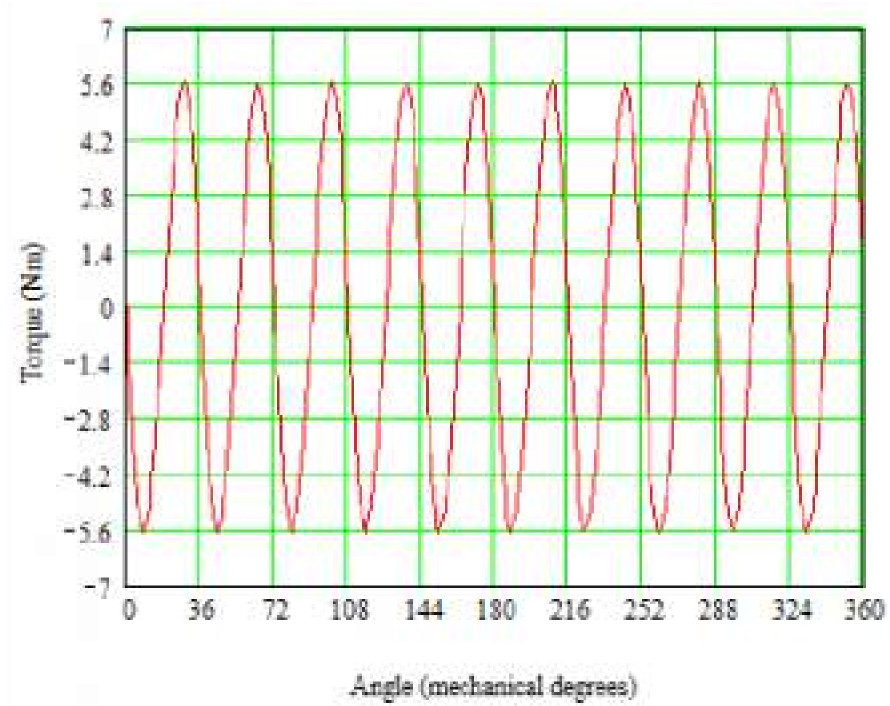


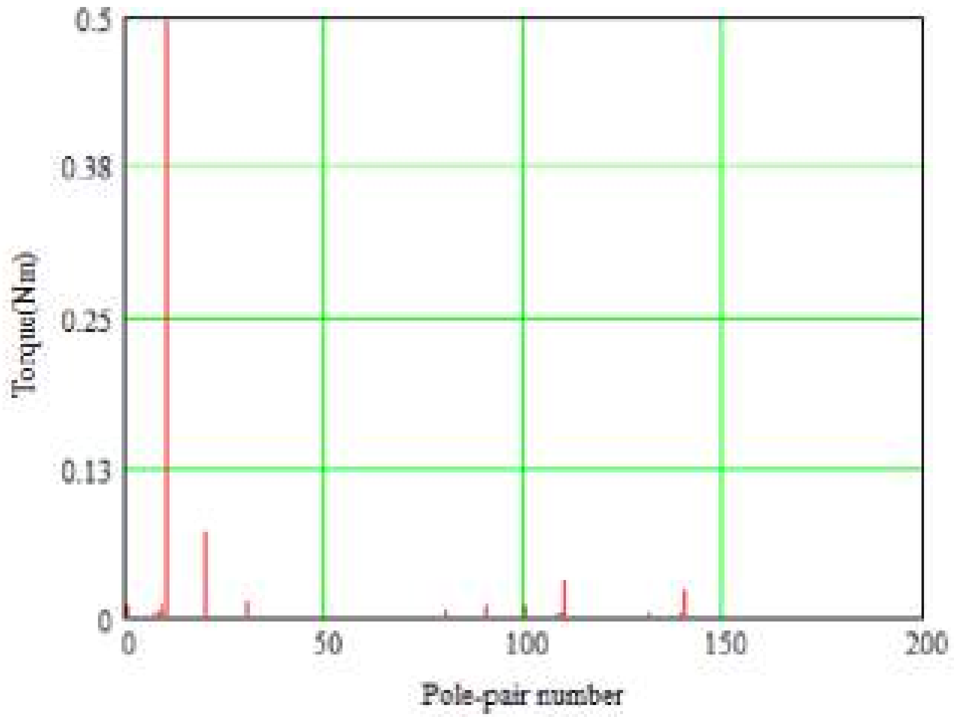
Figure 17. Harmonic content of magnetic torque at inner gap.

- Hamonic for p=4 contributes to the efficient torque
- Harmonic for p=56 contributes to the ripple torque
- How to find it ? ppcm(2*ph,ns)

Cogging torque:

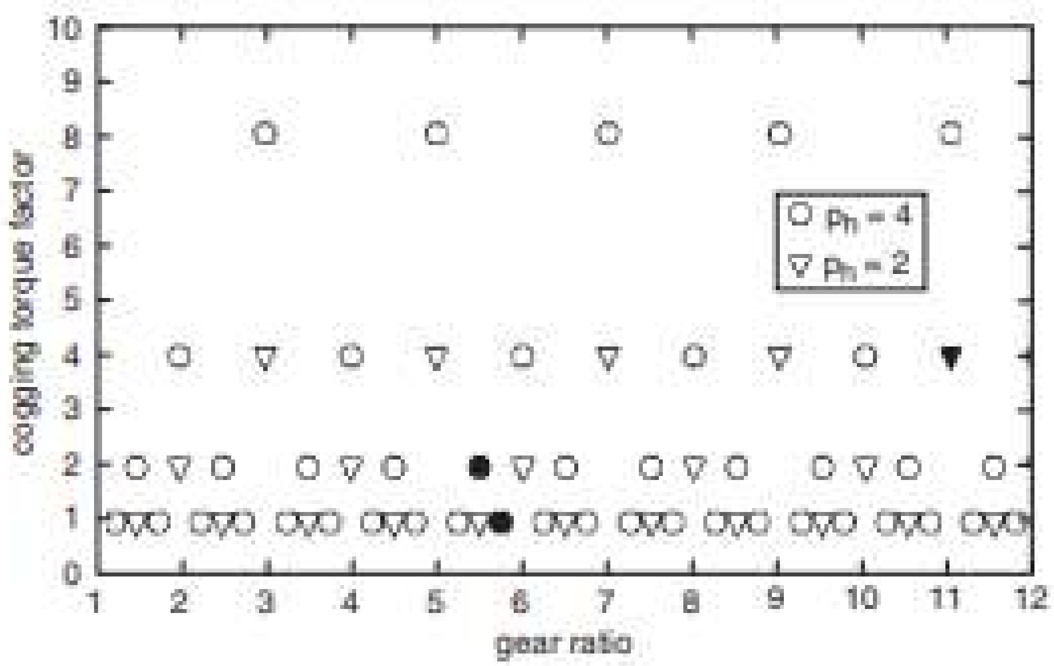
Torque on the outer rotor





- Hamonic for p=10 contributes to the efficient torque
- Harmonic for p=140 [ppcm(14,2*10)] contributes to the ripple torque

Cogging torque:



- Cogging factor : $K = 2 * \frac{p * Ns}{Nc}$

Nc = ppcm (2*p,Ns)

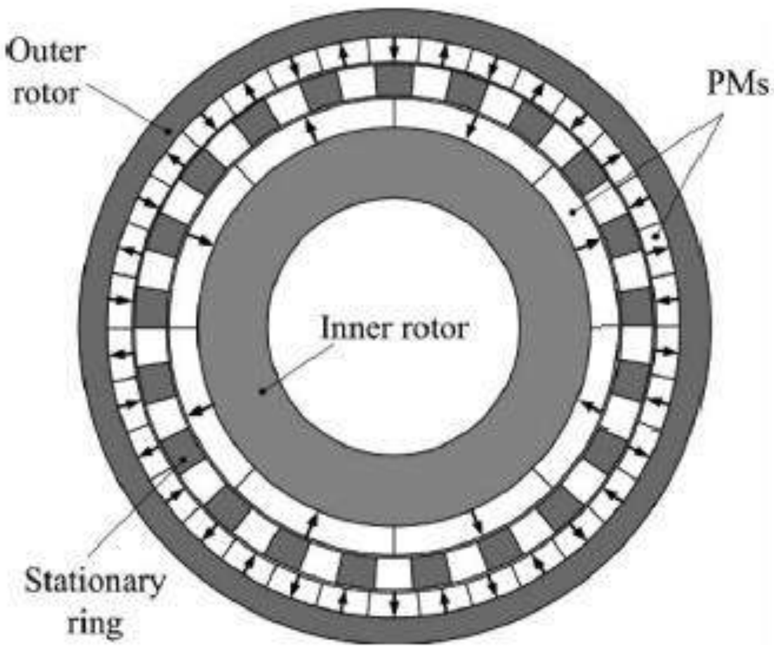
We have to minimize this factor to reduce the cogging torque

Optimum factor : K = 1

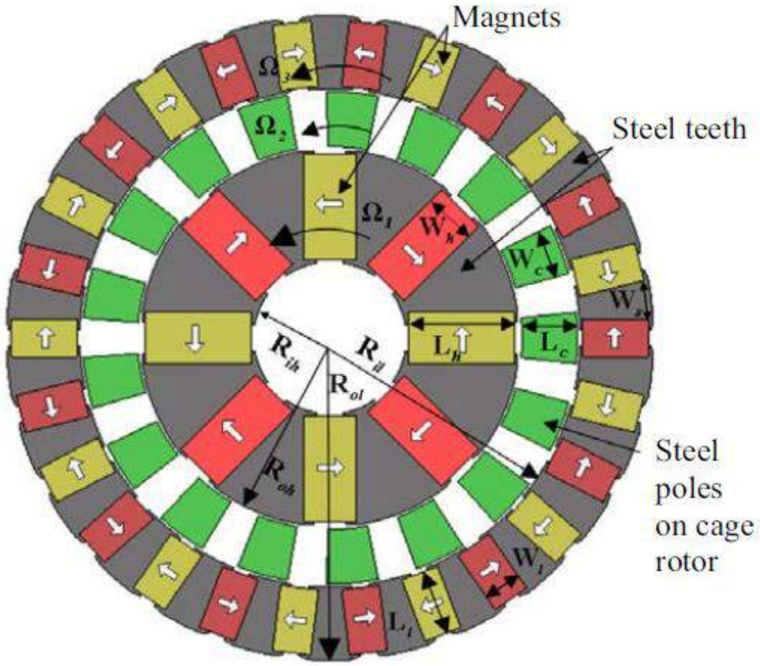
Harmonics : synthesis

- Each rotor with PM generates a magnetic flux
- Ferromagnetic pieces modulate the field to produce harmonics that can interract with the other rotor
  - Main harmonics interacting : harmonic 1 with fundamental
- Useful cogging torque produced at the good frequency + ripple cogging torque at higher frequencies
  - Good rule of thumb to reduce ripple : Cogging factor

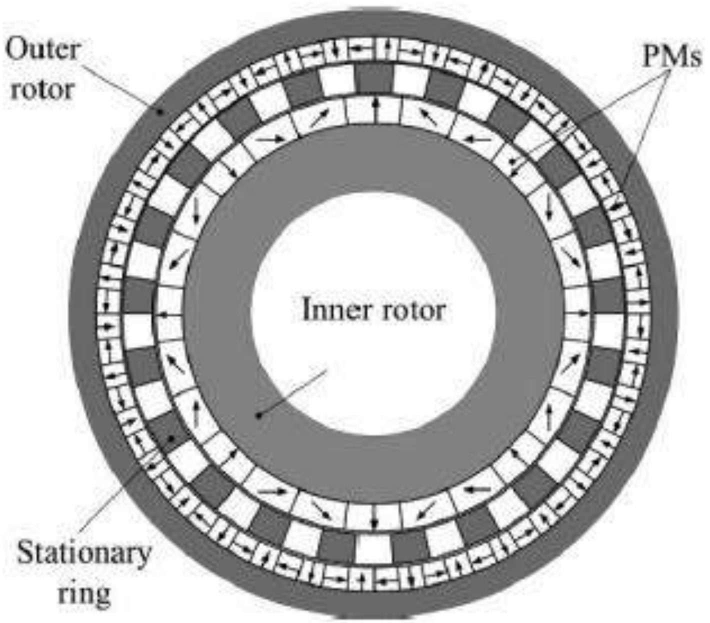
Different type of PM arrays



Surface mounted



Spoke type array



Halbach array

Halbach Permanent-Magnet Arrays

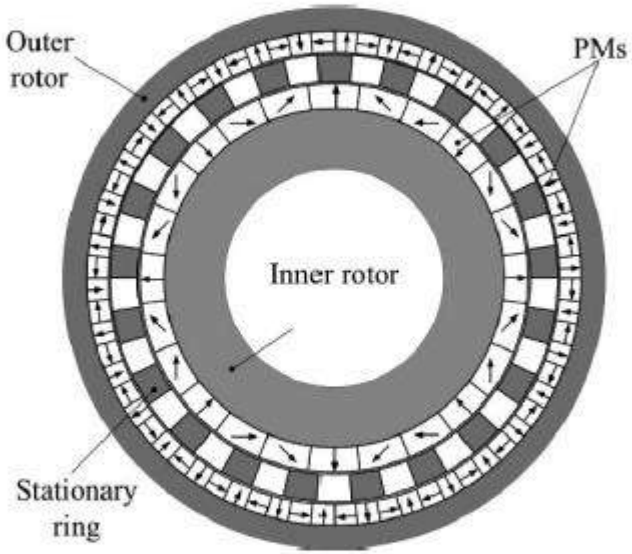
Drawback of conventionnal PM : high torques ripple
=> solution

Advantages :

- near-sinusoidal airgap flux density distribution
- strong field intensity in both air gaps
- good self-shielding magnetization
- High resulting torque density
- Low torque ripple / iron losses

- **Caracteristics :**

- $Ph = 4$
- $Pl = 17$
- $Ns = Ph + Pl = 21$



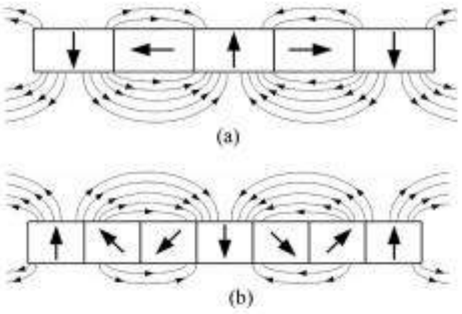


Fig. 3. Halbach PM arrays. (a) Two segments per pole. (b) Three segments per pole.

Halbach Permanent-Magnet Arrays

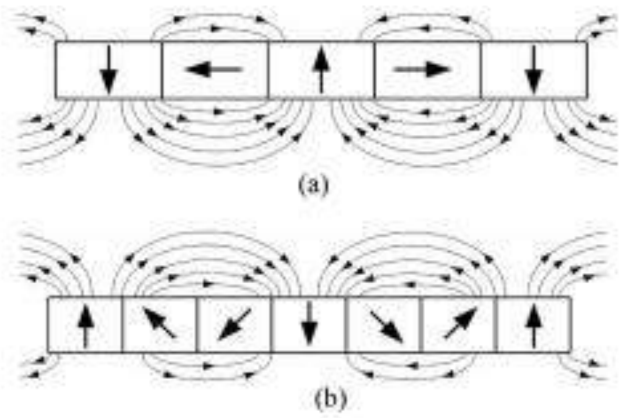


Fig. 3. Halbach PM arrays. (a) Two segments per pole. (b) Three segments per pole.

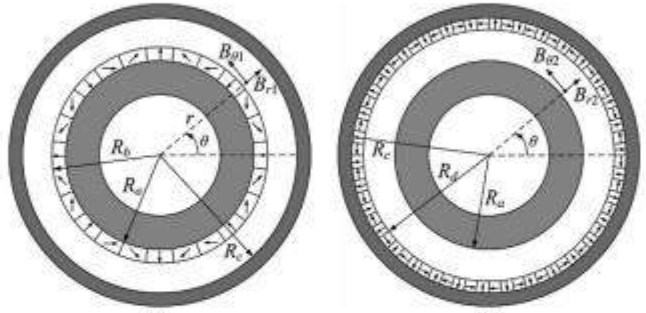
Choice of the number of segments per pole (NSP) :

<u>3 Consideration :</u>

- Nsp higher
  - sinusoidal flux densities
    - higher mean torque
    - help suppress cogging torques
  - Increasing of fabrication cost
- Different NSP values cause different magnetic field strengths

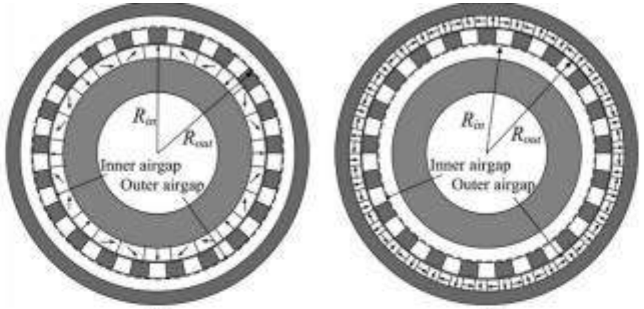
How to compute magnetic field / flux linkages & torque

- Principle of superposition :



(a) (b)

Fig. 5. Magnetic fields excited by rotors without stationary ring. (a) Inner rotor. (b) Outer rotor.



(a) (b)

Fig. 6. Magnetic fields excited by rotors with stationary ring. (a) Inner rotor. (b) Outer rotor.

<u>Without ferromagentic poles:</u>

- For the inner rotor : Br1
- For the outer rotor : Br2

Modulation by a factor λ (permeance)

<u>With ferromagentic poles:</u>

- For the inner rotor : Br1_in & Br2_in
- For the outer rotor : Br2_out & Br1_out

- Br_out = Br1_out + Br2_out
- Br_in = Br1_in + Br2_in

Halbach Permanent-Magnet Arrays

PERFORMANCE ANALYSIS :

Using time-stepping FEM

Assumptions : ph=4 / pl=17 / ns=21

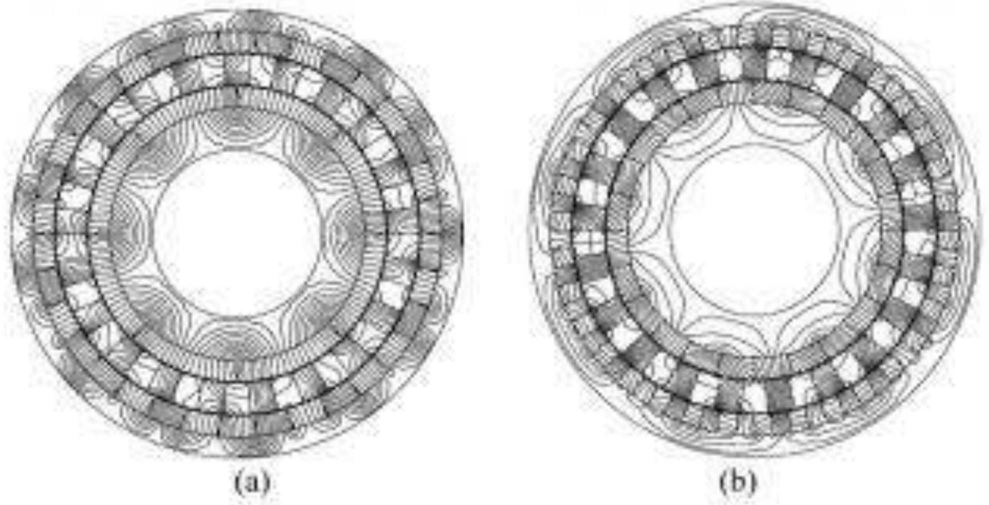


Fig. 7. Magnetic field distributions. (a) Conventional. (b) Proposed.

Note :

- much lower magnetic flux density for the HPMG in the inner/ outer rotor yoke
- Rotor yokes can be further diminished, hence reducing the overall weight and volume of the gear, as well as the inertias of the rotors

Comparison with the Conventional gear

- <u>In the inner air gap :</u>

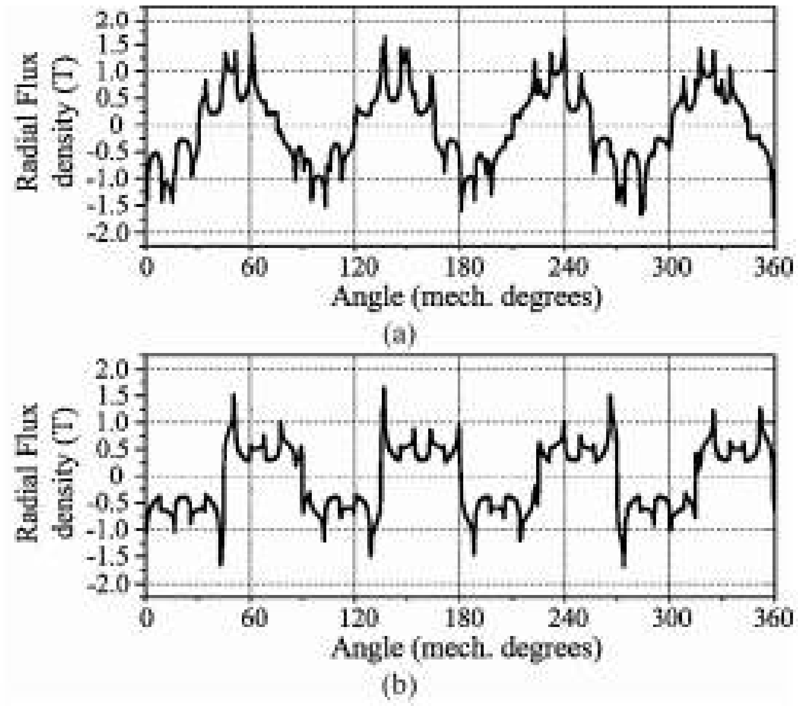


Fig. 8. Radial flux densities in inner airgap. (a) Proposed. (b) Conventional.

<u>Note :</u>

- Radial component more sinusoidal in the HPMG
- Higher value of the flux
- Higher torque

Comparison with the Conventional gear

Harmonic Spectrum in the inner air gap

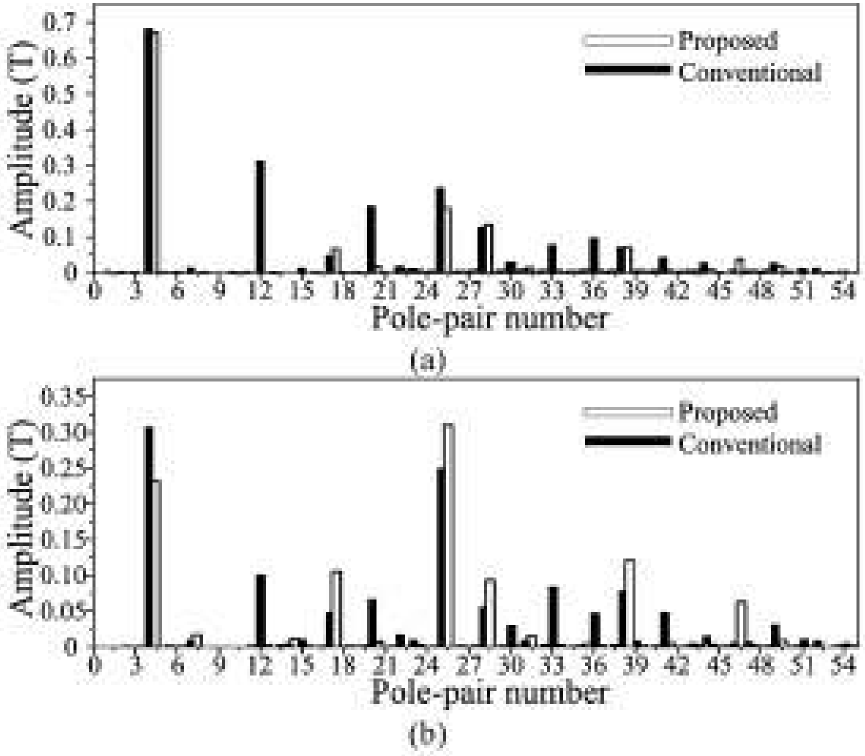


Fig. 10. Harmonic spectra of flux densities in inner airgap. (a) Radial. (b) Tangential.

Note :

- Pole-pair number in the harmonics components : $pijk = k * Ns + \mathrm{j} * \mathrm{pi}$

$$wijk = \frac{j * pi * wi}{k * Ns + j * pi}$$

Effective harmonics : p2-11 = 4 / p210 = 17 / p111=25

- Harmonics suppressed : p = 12 / p=20 / p=28 / p=33 / p=41

- Harmonic pole − pair number source of ripple : $p1jkm = k * Ns + j * m * p1$
  p1113=33 / p1115=41
- Harmonic Pole-pair number produce by the outer rotor responsible for iron losses (rotate at the same speed of $\omega 1$):
  p2 -133 = 12 / p2 -155 = 20 / p2 -177 = 28

$$\omega = \frac{j*m*p2}{k*Ns+j*m*p2} \times \omega 2$$

Comparison with the Conventional gear

Harmonic Spectrum in the outer air gap :

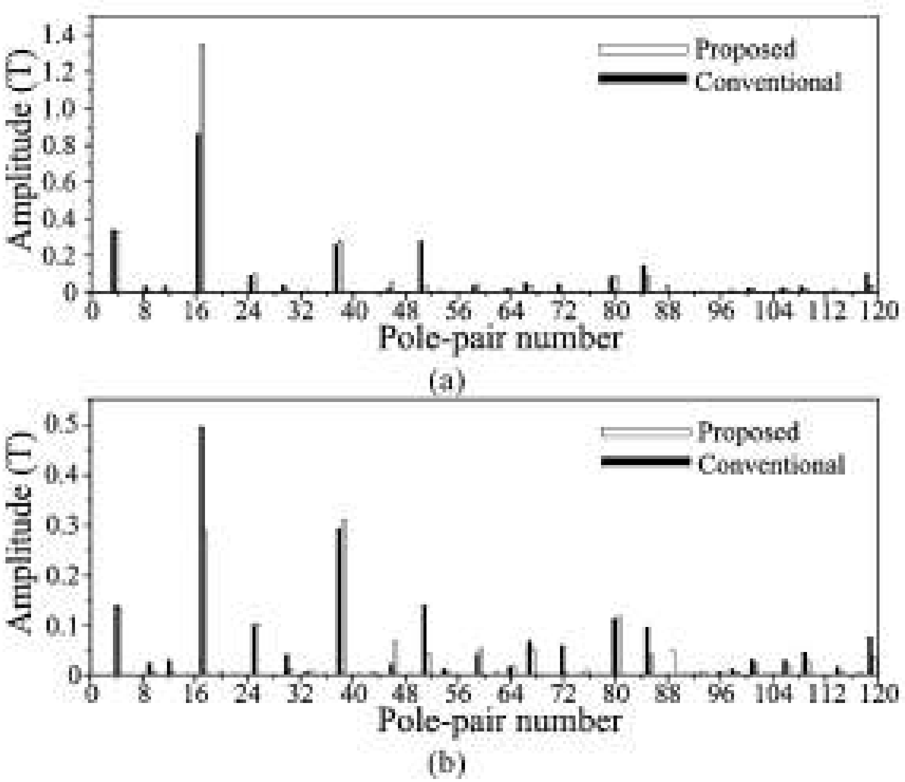


Fig. 13. Harmonic spectra of flux densities in outer airgap. (a) Radial. (b) Tangential.

<u>Note :</u>

- Effective harmonics : p = 25 / p = 17 / p112 =46
- Harmonics suppressed : p = 51 / 72 / 85 / 106 / 109
- Harmonics responsible for the ripple : $p2jkm = k * Ns + j * m * p2$

  p2113 =72 / p2115 = 106

- Harmonic Pole-pair number produce by the inner rotor responsible for iron losses (rotate at the same speed of $\omega 2$):

p = 51 / p = 85 / p = 109

Comparison with the Conventional gear

Torque on the inner / outer rotor

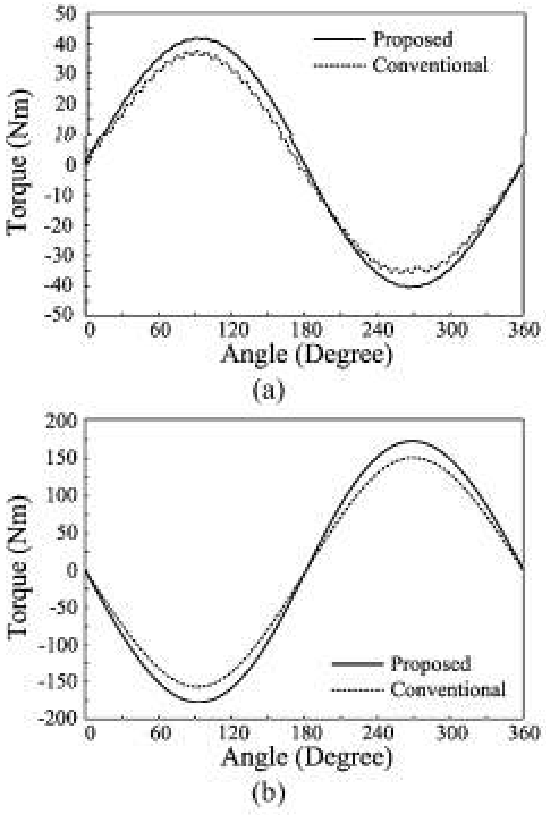


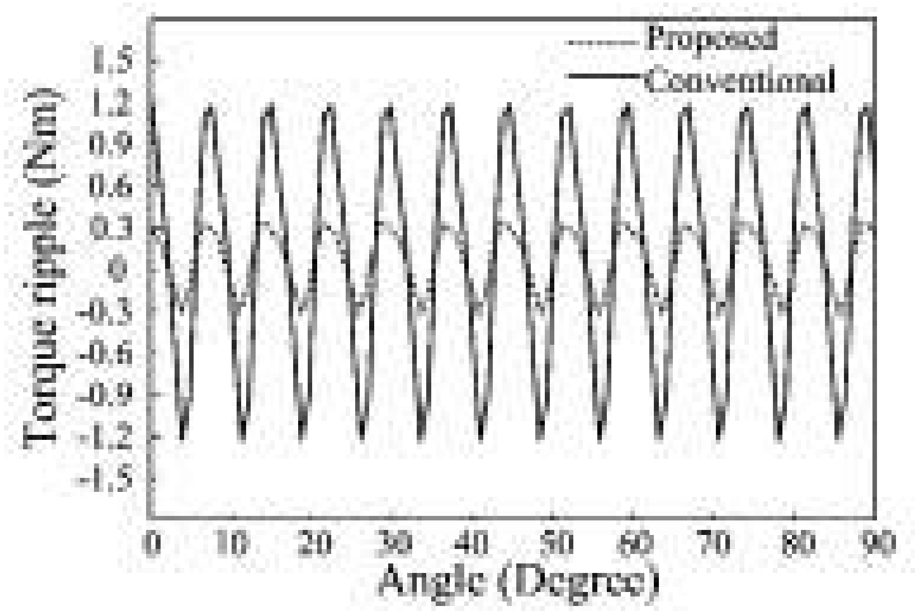
Fig. 14. Torque–angle curves. (a) Inner rotor. (b) Outer rotor.

Note :

- Technique : holding the outer rotor still and rotate inner rotor (simulation time – stepping FEM)
- Halback : greater mean value (offer 13% higher torque density)
- π difference between the phase angles of inner rotor and outer rotor curves
- if taking into account the reduction of the iron material, the proposed magnetic gear will have further improvement

Comparison with the Conventional gear

Cogging Torque on the inner rotor:



Note :

- Cogging torque in HPMG of 0.3 N・m compare to 1.2 N・m in the conventional magnetic gear
- 67% reduction in cogging torque.

Comparison with the Conventional gear

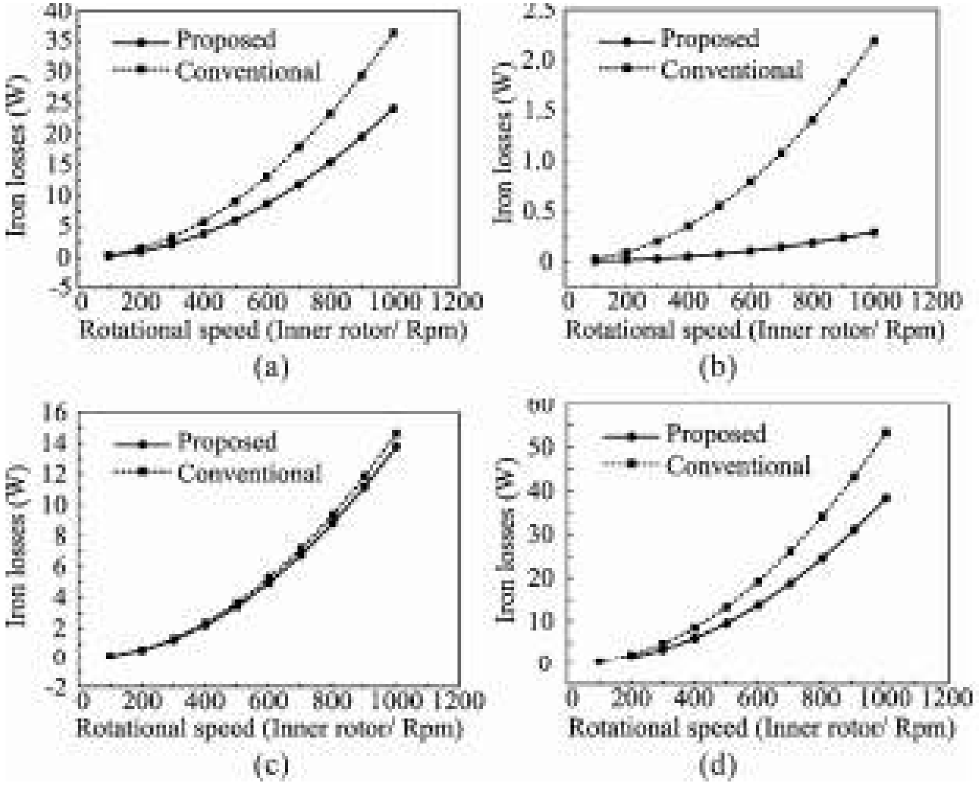


Fig. 16. Iron losses at different rotational speeds. (a) Stationary ring. (b) Inner rotor yoke. (c) Outer rotor yoke. (d) Total iron yoke.

- Type of losses : iron / stray losses
- Technique to measure it : at no load
- Notice : iron losses much lower in HPMG
  at 1000 rpm : reduction of 28% the total iron losses

PM arrays : Synthesis

- Possible to make different PM arrays
  - Conventional
  - Spoke type
  - Halbach
    - Near-sinusoidal airgap flux density distribution
    - Strong field intensity in both air gaps
    - G ood self-shielding magnetization
    - High resulting torque density
    - Low torque ripple / iron losses

Optimization of the shape factors

Objective

- Optimize the torque transmission through modifying ferromagnetic segments shape factor

1-D analytical model

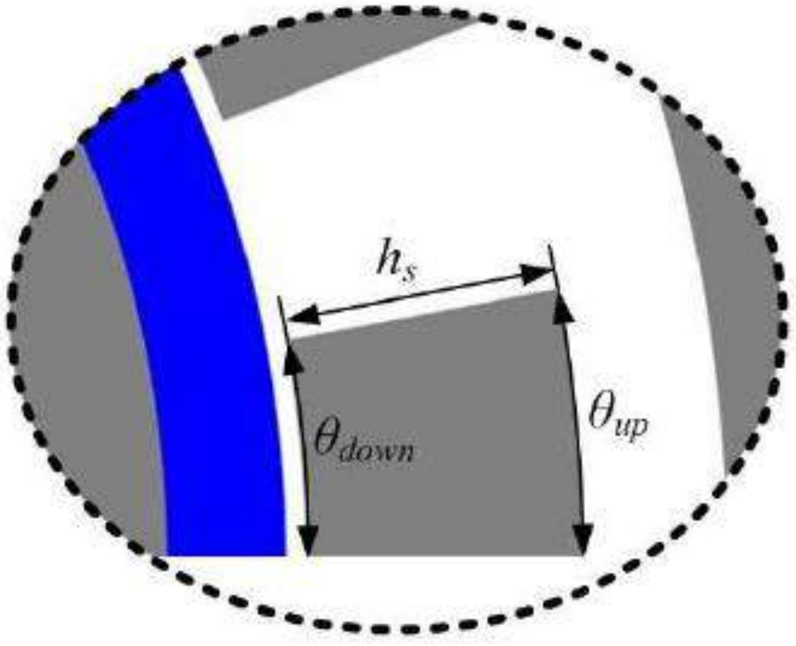
- Good for analysing modulating effect and working principle
- Not precise enough for optimization

FEM

- Very precise
- Big computational cost

Response Surface Methodology

- Good compromise



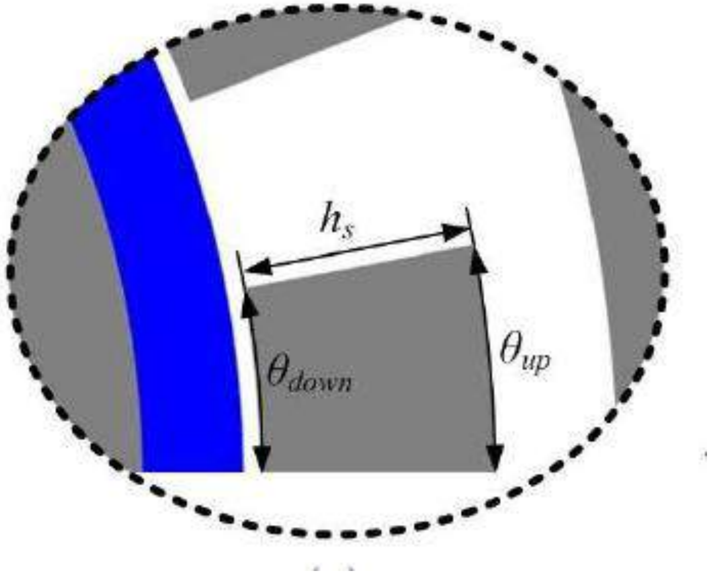
Shape factors of the ferromagnetic segments

Response surface methodology (RSM)

Statistical technique for finding the best-fitted relationship between the design variables and the response

Develop a second-order model to approximate the relationship between Y the maximum pull-out torque and the design variables X :

$$Y = f(X) \approx \beta_0 + \sum_{j=1}^{3} \beta_j x_j + \sum_{i,j=1}^{3} \beta_{ij} x_i x_j + \epsilon$$



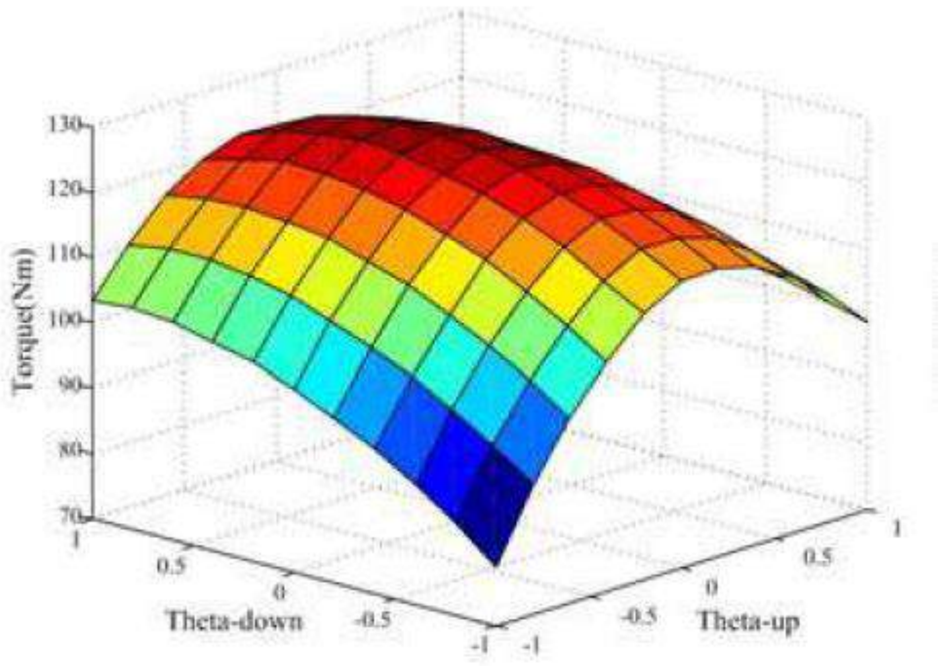
Design variables and scaled units.

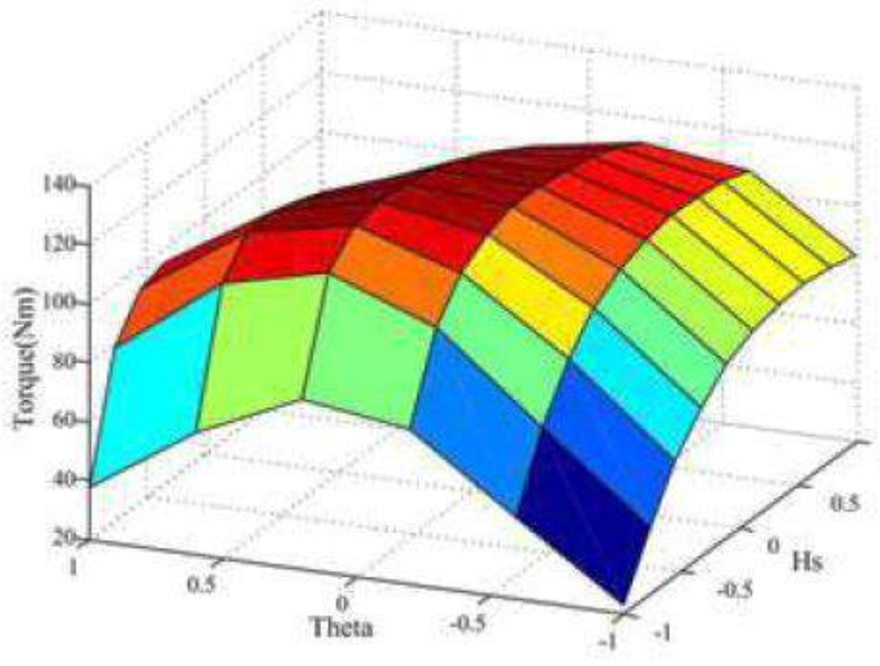
h_s/x_1	$3\,\mathrm{mm}/-1$	$16.5\,\mathrm{mm}/0$	$30\,\mathrm{mm}/1$
θ_{up}/x_2	$3\,\mathrm{Deg.}/-1$	$10.5\,\mathrm{Deg.}/0$	$18\,\mathrm{Deg.}/1$
θ_{up}/x_2	$3\,\mathrm{Deg.}/-1$	$10.5\,\mathrm{Deg.}/0$	$18\,\mathrm{Deg.}/1$

Response surface methodology (RSM)

Statistical technique for finding the best-fitted relationship between the design variables and the response

FEM → Least-square method $\hat{\beta} = (X^T X)^{-1} X^T Y$ → $Y = f(X) \approx \beta_0 + \sum_{j=1}^{3} \beta_j x_j + \sum_{i,j=1}^{3} \beta_{ij} x_i x_j + \epsilon$ → ANOVA





Response surface methodology (RSM)

Statistical technique for finding the best-fitted relationship between the design variables and the response

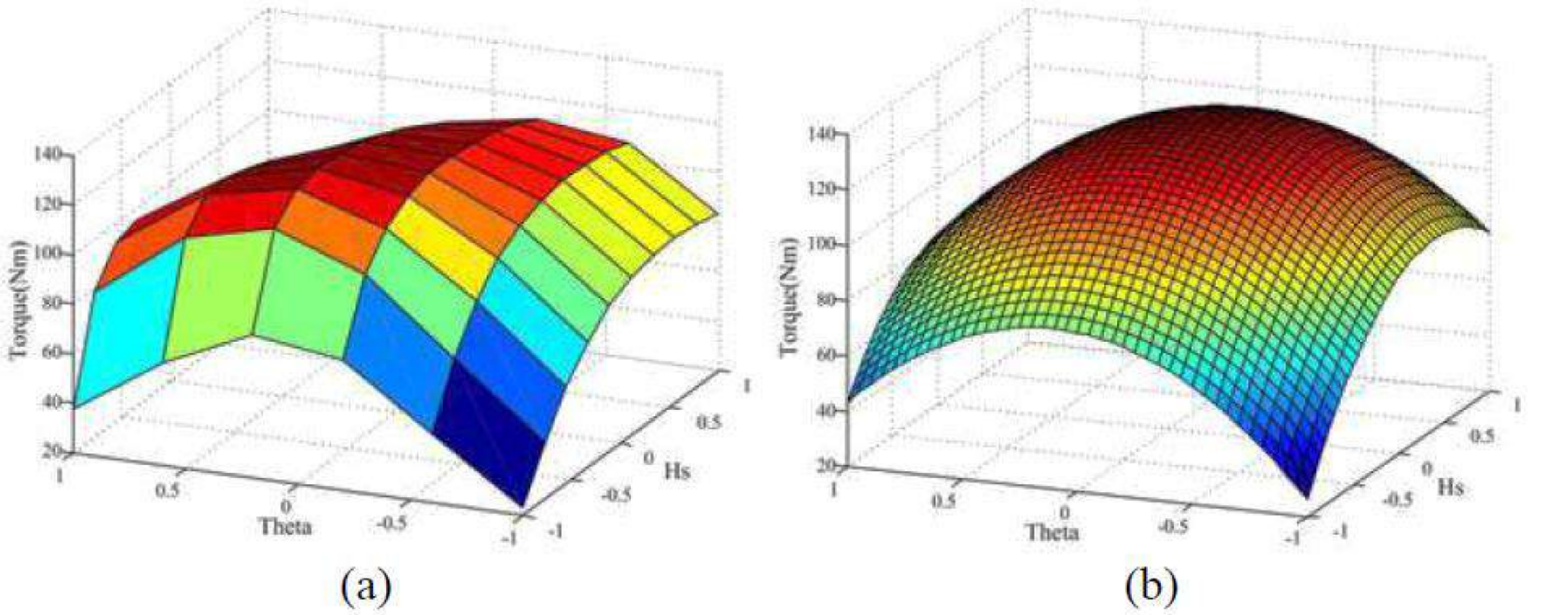


Figure 4. Comparison of response surfaces over $\{\theta_{up} = \theta_{down} \in [3, 18],\ h_s \in [3, 30]\}$. (a) True value. (b) Fitted value.

Response surface methodology (RSM)

Statistical technique for finding the best-fitted relationship between the design variables and the response

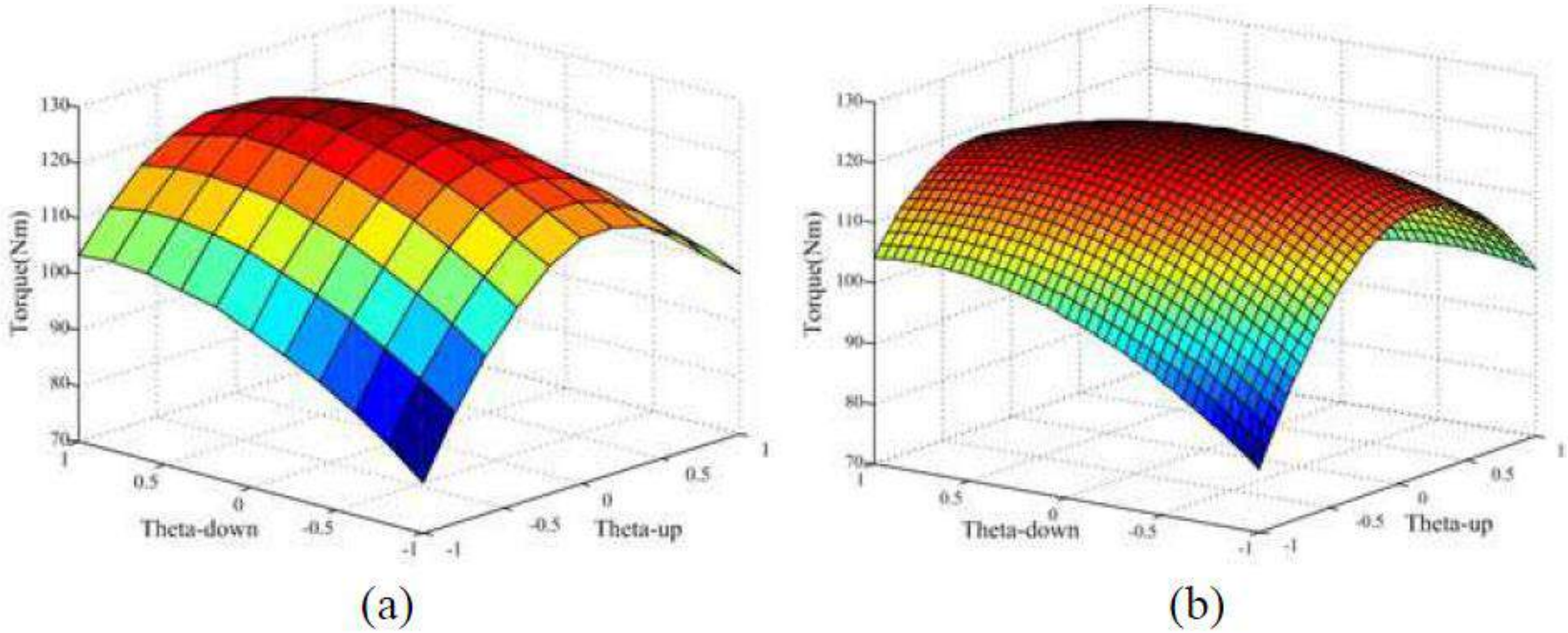
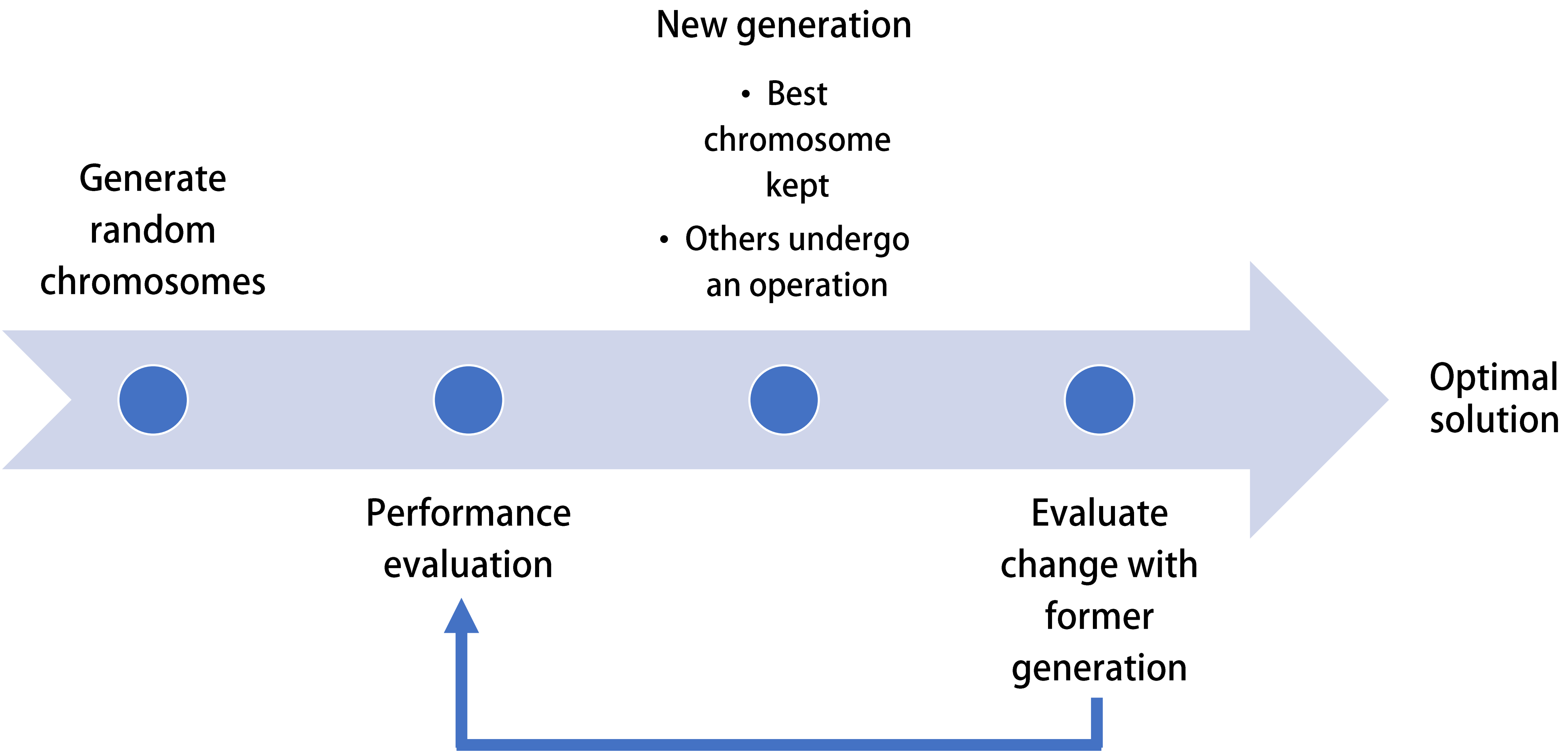


Figure 5. Comparison of response surfaces over $\{\theta_{up} \in [3,\ 18],\ \theta_{down} \in [3,\ 18],\ h_s = 15\}$. (a) True value. (b) Fitted value.

Optimization with genetic methods (NSGA)

*Genetic algorithm is an optimization procedure inspired by **natural selection.***
*It relies on **bio-inspired operators** such as mutation, crossover and selection*



Optimization with genetic methods

Optimization problem

$$\min -Y = -f(X)\ s.t.\left\{X = [x_1, x_2, x_3]^T;\ x_1 \in [-1,1]; x_2 \in [-1,1]; x_3 \in [-1,1]\right\}$$

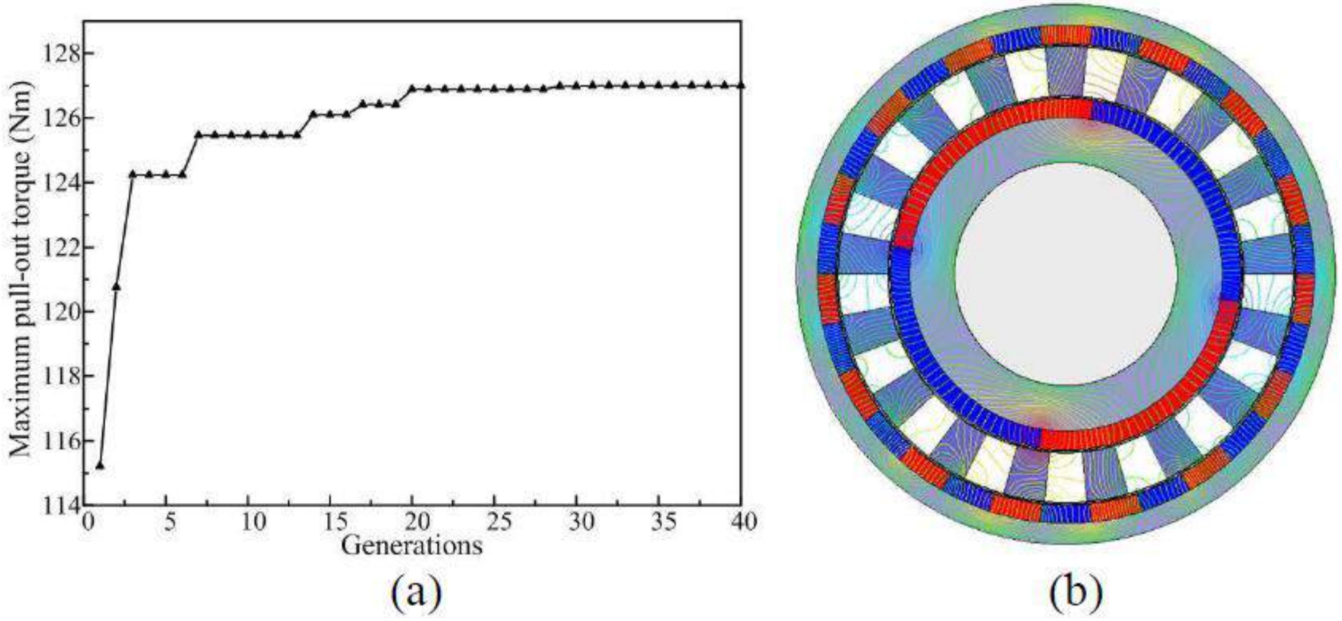
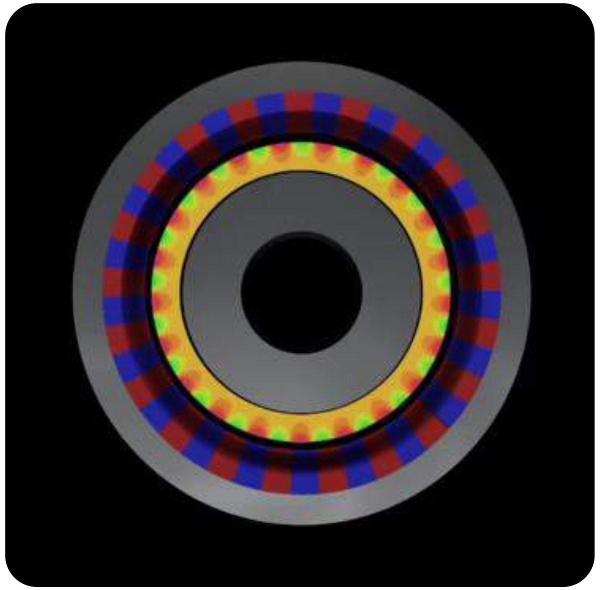
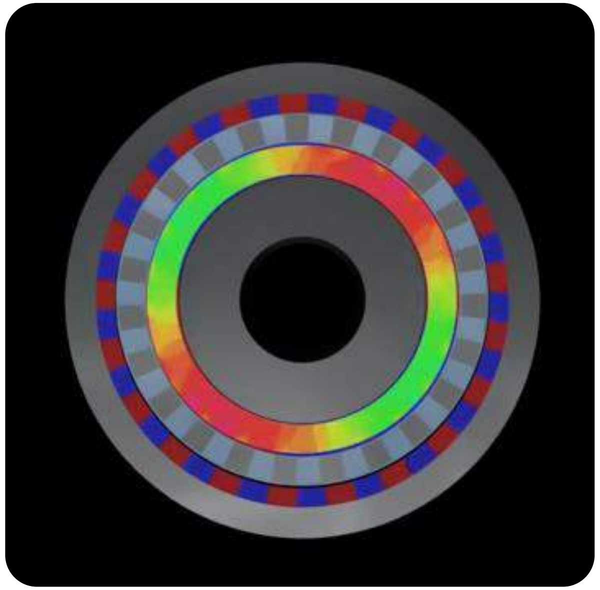


Figure 6. Optimization using genetic algorithm. (a) Maximum pullout torque at each generation. (b) Flux line distribution in optimal case.

Solution	
θ_{up}	9,819°
θ_{down}	11,025°
h_s	19,955 mm
$T_{max,model}$	127,209 Nm
$T_{max,FEM}$	126,216 Nm

Conclusion





- Interesting alternative to mechanical gears
  - Mechanical isolation possible
  - Self-protection when overloaded
  - No need for lubrication and less maintenance
- Works thanks to the modulation of the magnetic field through ferromagnetic segments
  - Number of pair of poles allows to chose the gear ratio
- The arrangement of PM array may increase performances of the gear
  - Conventional array
  - Spoke type array
  - Halbach array
- The arrangement of ferromagnetic pieces may increase performances of the gear
  - Torque can be optimise by varying shape factor.

Thank you for your attention