Review and Design of High-Speed Magnetic Couplings

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Abstract

This paper focuses on the first steps of a project "High-Speed Magnetic Coupling" (HSMC). The project is a part of another project for generating electricity by a jet engine. The purpose of the HSMC is to couple the jet engine and a high-speed permanent magnet synchronous motor (PMSM) whose rotation speed and torque are around 100,000 rpm and 0.1 to 1 Nm, respectively. Firstly, literature reviews of magnetic couplings (MCs) are introduced. It is depicted that both analytically and experimentally, how various parameters such as a number of poles, alignments, etc., affect other parameters. Then, based on the reviews, fundamental designs of MCs for experimental testing are proposed. The results of the practical experiments are shown revealing doubts about how unconventional MCs behave and if they would be like the introduced data. Moreover, some possible designs for the HSMC are discussed by taking into account the introduced parameters and the experimental results, as well as other industrial and commercial MCs.

Keywords: Magnetic; Coupling; Review; Design; Generator; High-speed

1. Introduction

This project is a part of another project for generating electricity by a jet engine. The purpose of the HSMC is to couple the jet engine and a high-speed PMSM safely whose rotation speed and torque are around 100,000 rpm and 0.1 to 1 Nm, respectively. The task of this paper is to introduce the basic properties of the MCs and suggest designing the HSMC based on the derived data. There are three chapters in the paper. Firstly, various parameters of MCs, which derived by simulations and experiments, are shown from other sources. Even though the scale of values is different from the project, it is possible to see the trend. Secondly, actual experiments are done referring and comparing the introduced results. Lastly, several fundamental possible designing ideas are suggested by considering all gained data and results.

Figure 1 shows the torques depending on the air gap length by using 2D analytical models and 3D simulations. [1] As the air gap length increases, the torque decreases obviously on any simulations. The air gap also determines the speed response of the driving and driven MCs. Oscillations can be seen in the speed response depending on time generally. And closer air gap has a quicker response which means the driven one follows another with smaller angular deviations. However, the deviation disappears after some time when the synchronisation proceeds. For the synchronisation, it is mandatory to take a while to starting-up otherwise the synchronisation is lost and the driven one stops rotating. As well as the starting-up, an abrupt loading on the couplings is a factor to stop the rotation unless there is enough transferable torque to get back to the steady-state. Not only the air gap but also various parameters affect the transferable torque and one of them is angular or radial misalignments of MCs.

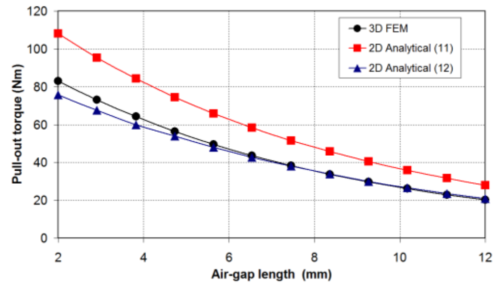

Figure 1. *Measured and computed static torque versus the angular displacement [1]*

In figure 2, there are various curves with the air gaps for the transferable torque depending on the number of pole pairs. [2] A smaller number of the pairs, less torque. However, the torque increases until some points and goes down gradually with the larger number of the pairs. Moreover, the transferable torque is decided by a ratio between the number of pole pairs and the magnet angular width. Therefore, it does not mean a greater number of magnets, more transferable torque.

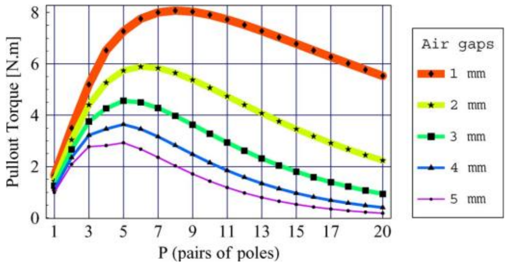

Figure 2. *Torque versus the number of pole pairs [2]*

Regarding eddy current (EC) in axial MCs, there is a relationship that it grows proportionally as the number of rotations rises. Hence, its losses also increase proportionally. [3] Furthermore, radial MCs have the same tendency

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as axial ones. In the radial MCs, a type of them is proposed and called as Halbach array. It can enhance the magnetic field dramatically towards one side. There are several kinds of it depending on the number of sections in each magnet. There is a fact again that EC losses are enlarged as the rotation increases as well as EC losses are higher with a greater number of the sections. [4]

2. Experiments

Considering also the data introduced in the previous chapter, some experiments are done. Firstly, unconventional radial MC’s behaviours are observed. Secondly, conventional axial and radial MC’s behaviours with and without various loads are observed. Finally, the behaviours of those MCs when giving an abrupt loading are observed.

2.1. Experimental setup

In figure 3, instruments used in the experiment are listed from the left side in the figure and as below.

- Power supply; LW-K3010D
- Electrical Speed Controller (ESC): 2-3S, max. 20 A
- Brushless DC (BLDC) motor: motor: FOXY G3 C2208 1200 KV, 2-3S, max. 17 A, max. 145 W (max. speed around 14400 rpm)
- 5 types of MCs
- DC motor: MIG480 7.2 V RACE, max. 10 A
- Resistors: 1, 0.1 and 0.01 ohm
- Photo tachometer: UT-372
- Oscilloscope: FNIRSI-1013D
- Multi-meters: XL830L

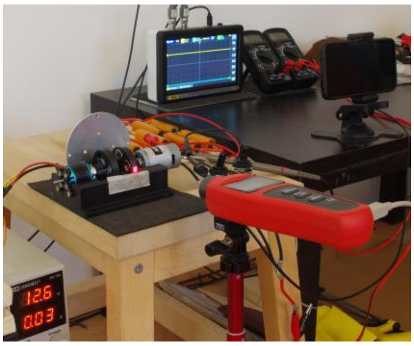

Figure 3. *Speed responses to an overload condition*

The BLDC motor is connected to one of the various MCs and it transfers the torque to the DC motor. The DC motor is connected to one of the resisters and the multi-meters measure the voltage and current flowing in the resistor. The photo tachometer measures the rotational speed at the coupling on the DC motor side. The oscilloscope displays the voltage at the BLDC motor input and DC motor output. The list of MC arrangements is as below. The couplings are produced by 3D printing with PLA material with 80 % infilling. And figure 4 to 9 respectively depict the utilised coupling structures and their general dimensions. The method of how the MCs is connected is by the friction and transition fitting simply. Figure 10 shows the overview of manufactured MCs for the experiments with their fit magnets.

1. Radial, male 4 poles, female 4 poles, 3 mm air gap (not between magnets but couplings, see orange lines in Figure 4 and 5) (N35 Neodymium (NdFeB) 20*10*2 rectangular magnets)
2. Radial, male 4 poles, female 6 poles, 3 mm air gap (not between magnets but couplings) (N35 NdFeB 20*10*2 rectangular magnets)
3. Axial, 4 poles each, 13 mm air gap (NdFeB 15 mm diameter, 5 mm hole diameter, 3 mm thickness circular magnets)
4. Axial, 4 poles each, 6 mm air gap (NdFeB 15 mm diameter, 5 mm hole diameter, 3 mm thickness circular magnets)
5. Radial, male 6 poles, female 6 poles, 2 mm air gap (not between magnets but couplings) (N35 NdFeB 20*10*2 rectangular magnets)

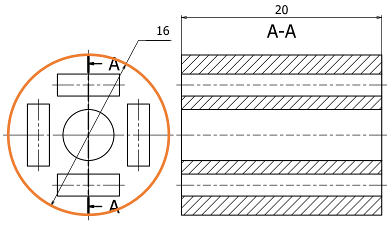

Figure 4. *Radial, male 4 poles (arrangement 1 and 2)*

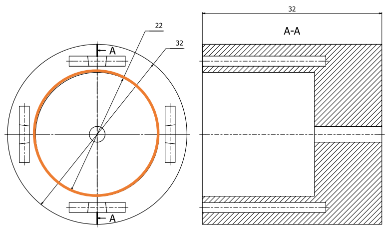

Figure 5. *Radial, female 4 poles (arrangement 1)*

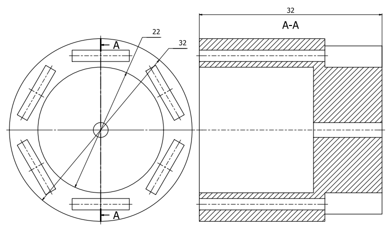

Figure 6. *Radial, female 6 poles (arrangement 2)*

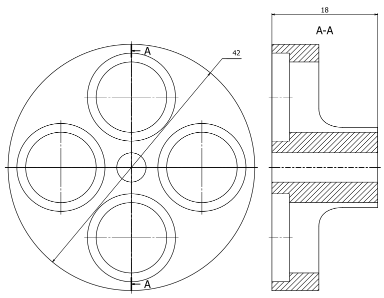

Figure 7. *Axial, 4 poles (arrangement 3 and 4)*

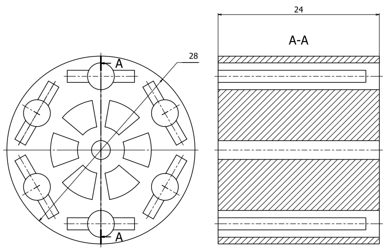

Figure 8. *Radial, male 6 poles (arrangement 5)*

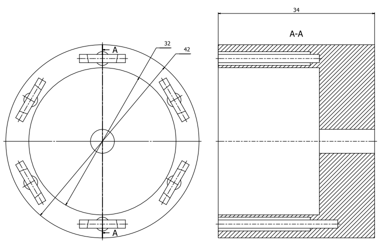

Figure 9. *Radial, female 6 poles (arrangement 5)*

Figure 10. *Overview of manufactured MCs for the experiments*

2.2. Results

At first, the arrangement 1 and 2 which are unconventional MCs are not successful in synchronising the rotation from the starting-up or very beginning of rotating even though also starting up gradually since they do not transfer the torque well or smoothly. Moreover, it is found the magnets must be covered or integrated into the couplings otherwise they could blow off and it is extremely dangerous. Due to the low precision of my 3D printer, I have glued the magnets.

Figure 11, 12 and 13 represent the maximum speed, the maximum voltage, and the maximum current of the DC motor without resistors, with 1, 0.1 and 0.01 ohm. The 0.01 ohm resistor is only for arrangement 5.

The maximum speed for all couplings is almost the same around 14000 rpm. After giving the resistor loads, arrangement 3 dropped the speed significantly to around 6000 rpm. Meanwhile, others kept the value around 14000 rpm. Compared to the arrangement 4 and 5, the values of the arrangement 4 are higher generally except the no-load test.

For the maximum voltage, the trend is almost the same as the previous one and arrangement 4 produces a larger voltage than arrangement 5. The only differences are the arrangement 3 makes the voltage the most when without loading. And the voltage decreases slightly as the load increases.

Finally, regarding the maximum current, the trend is a little different. As the load grows, the current rises and this is logical from ohm's law.

It is possible to say as the air gap becomes smaller, the transferable torque becomes larger and keeps the speed constantly.

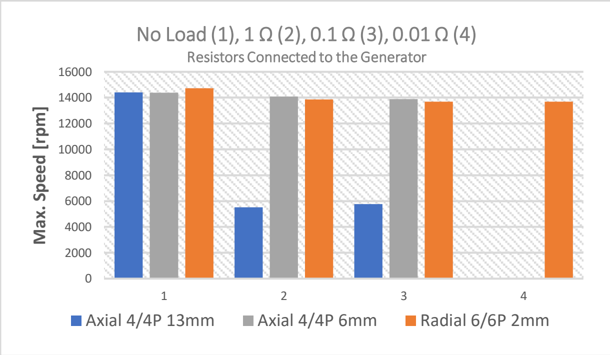

Figure 11. *Maximum speed*

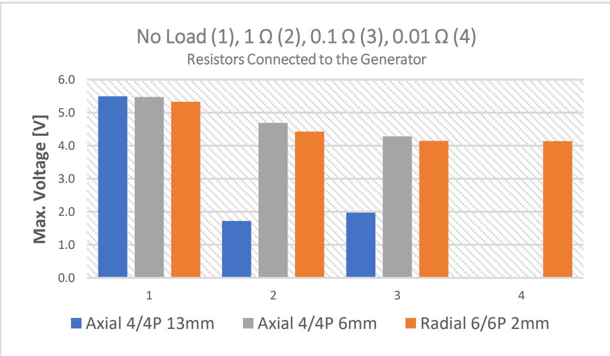

Figure 12. *Maximum voltage*

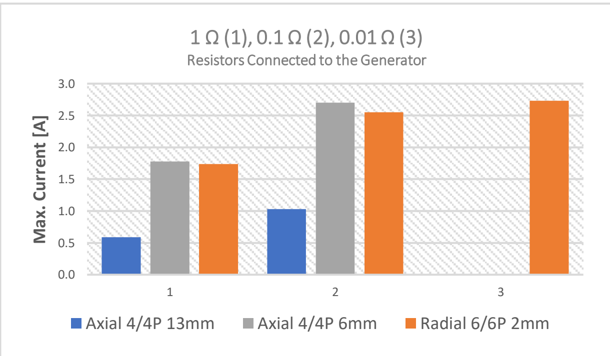

Figure 13. *Maximum current*

Figure 14, 15 and 16 depict the time response to the rotational speed when obtaining an abrupt load 0.1 ohm for the arrangement 3, 4 and 5, respectively.

Arrangement 3 in figure 14 shows losing the synchronisation after getting the abrupt load.

Arrangement 4 in figure 15 displays keeping the synchronisation as well as arrangement 5 in figure 16.

It is obvious again that as the air gap length decreases, the transferable torque gets larger and keeps the rotation constantly.

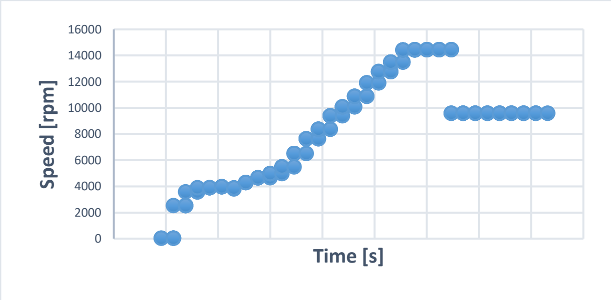

Figure 14. *Axial 13 mm 0.1R (arrangement 3)*

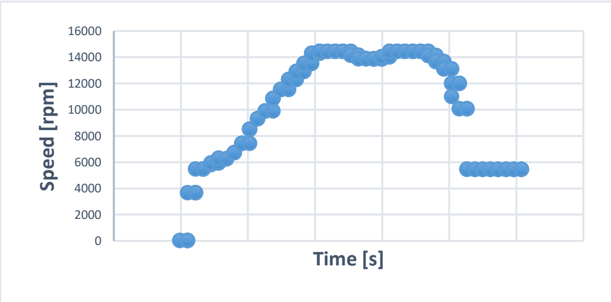

Figure 15. *Axial 6 mm 0.1R (arrangement 4)*

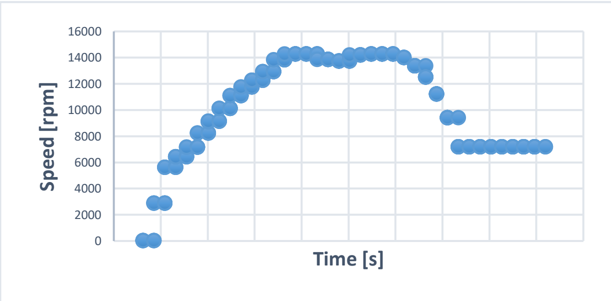

Figure 16. *Radial 2 mm 0.1R (arrangement 5)*

Figure 17 shows a screenshot of a video for the experiment during arrangement 5 without loading. As can be seen on the left top, the oscilloscope projects the voltage signal shapes of the BLDC motor input (top) and the DC motor output (bottom) at the maximum speed, 14723 rpm. The signal on the top has the periodic wave for driving BLDC motors. On the other hand, another one is flat entirely with small periodic drops and spikes for generating electricity. An interesting point is the periods for both signals are not the same and the DC motor one has a slightly longer period.

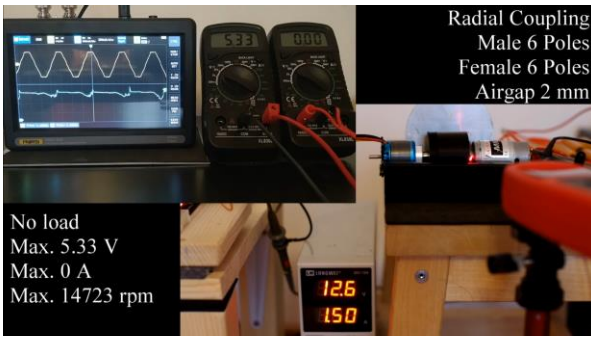

Figure 17. *Screenshot of the experiment for arrangement 5*

3. Fundamental ideas of designing the MC

3.1. Important factors

Three essential factors must consider in designing the MC as listed below.

1. Mechanical deformations

To avoid severe damages and resonances, the shape must be kept and even a small deformation must never be caused especially at high-speed rotations.

2. Moment of inertia

The rotational energy increase by the squared of angular velocity as described in equation (1). At high speed, the effect of the moment of inertia is quite huge as well.

$$E_R = \frac{1}{2} I \, \omega^2 \qquad (1)$$

Where E_R is rotational energy, I is a moment of inertia and ω is angular velocity.

The moment of inertia for cylinders is expressed as equation (2) in general. Especially, the moment of inertia for hollow cylinders is described as the equation (3). [5]

$$I = \int r^2 \, dm \qquad (2)$$

$$I = \frac{1}{8} m(D^2 + d^2) \qquad (3)$$

Where m is mass, D is outer diameter and d is inner diameter.

3. Temperature

The temperature would rise as the rotation speed increases due to increasing of EC in the MC and it causes demagnetisation of the magnets.

3.2. Concreate and fundamental designing ideas

Considering all introduced data in the previous chapters, the concrete designing ideas for MC are listed as follow.

1. Designing the radial shape and thinner as much as possible

The reason is to reduce the moment of inertia and to reduce EC. [6]

2. Designing shorter length as much as possible unless losing the required transferable torque

It is because that bending could be caused due to the centrifugal force by high-speed rotation. Therefore, serious resonances or oscillations could be followed.

3. Covering or integrating the magnets

To avoid blowing the magnets off.

4. Choosing soft magnetic materials with high stiffness property and lightweight for magnet holder

For achieving high speed and efficiency in magnetic flux. The candidate materials are SUS410L, Fe-Ni, Fe-3%Si, Fe-Co and so on. [7] Including the materials, magnetic property lists for commonly utilised soft magnetic materials are introduced in table 1.

Table 1. *Soft magnet properties [8]*

Alloy System	Typical Density (g / cm3)	Approx. Relative Cost	μmax	Hc (kA / m)	Bmax (T)	Resistivity (μΩcm)
Fe	6.8 - 7.2	1	1800 - 3500	0.12 - 0.2	1.0 - 1.3	10
Fe-P	6.7 - 7.4	1.2	2500 - 6000	0.10 - 0.16	1.0 - 1.4	30
Fe-Si	6.8	1.4	2000 - 5000	0.02 - 0.08	0.8 - 1.1	60
400SS	5.9 - 6.5	3.5	500 - 1000	0.12 - 0.24	0.6 - 0.8	50
50Ni/50Fe	7.2 - 7.6	10	5000 - 15000	0.01 - 0.04	0.9 - 1.4	45

5. Designing for flowing less EC by making layer structures

To prevent heat generation by EC loss, it is better to have a smaller volume of each element by making layers and increasing its resistance. [9, 10]

6. Implementing an efficient cooling mechanism

One of the ways is to divide the magnets as many as possible and increasing the exposed surfaces to the air. [11]

7. Utilising samarium–cobalt (SmCo) magnets

Table 2 introduces the properties of commonly utilised permanent magnets.

Table 2. *Permanent magnet properties [12]*

Type	Remanence [Br]	Coercive Field [Bhc]	Coercive Field [Ihc]	The Maximum Energy Product [BH]	Curie Temperature
	(mT)	(kA / m)	(kA / m)	(kJ / m3)	℃
Anisotropy Ferrite	390 - 410	238.7 - 270.5	242.7 - 282.5	28.7 - 31.9	450
Neodymium	1230 - 1290	836 - 995	> 876	279 - 310	300
Samarium-cobalt	980 - 1060	477 - 637	557 - 875	175 - 207	750
Alnico	1250 - 1300	47.7 - 52.5	0	38.2 - 43.8	860

To avoid the demagnetising by the increase of temperatures at high-speed rotation, utilising SmCo is a reasonable selection since it has an exceedingly high Curie temperature and the second highest magnetic energy after NdFeB. However, it is important to realise Curie temperature and the common operating temperatures of magnets are different, and the operating temperature is much less. [13, 14] For realising the cost by weight ratio and difficulty of machining, SmCo is the most expensive and relatively difficult to machine among the introduced permanent magnets. [15]

Compared to NdFeB and SmCo, the NdFeB has good properties in its noticeably high mechanical and magnetic strength, relatively low cost by weight and relatively easy to machine. Meanwhile, the disadvantages are its low operatable temperature and oxidation. Considering SmCo, it is superior at its high magnetic strength, high-temperature operatable and no protection is required for oxidation. On the other hand, the challenging points are it is greatly brittle and hard to machine and highly costing material. [16-18]

Table 3 represents the mechanical properties of NdFeB and SmCo. The densities and compressive strength have close values. However, NdFeB has better bending strength and higher resistance which are essential factors as already mentioned.

Table 3. *Mechanical Properties [19, 20]*

Density	Bending Strength	Compressive Strength	Electrical Resistivity	Coeff. Of Thermal Expansion		Curie Temperature
(kg / m3)	(kg / m2)	(kg / m2)	(Ωm)	/ / M	” ´M	(°C)
Neodymium Iron Boron						
7.6 x 103	2.95 x 103	9.6 x 103	1.4 x 10-6	7.9 x 10-6	-1.7 x 10-6	345
Samarium Cobalt						
8.4 x 103	1.2 x 103	9.1 x 103	0.8 x 10-6	9.2 x 10-6	11.8 x 10-6	825
/ / M Parallel to magnetic orientation,” ´M Perpendicular to magnetic orientation						

8. Applying Halbach array for the magnets

The array can reduce the mass and enhance the magnetic field which could lead to high efficiency in load torque transferring. [21, 22] Figure 18 represents the magnetic field of a normal array (left) and Halbach array (right). It can be seen the magnetic field is only on one side and enhance the intensity.

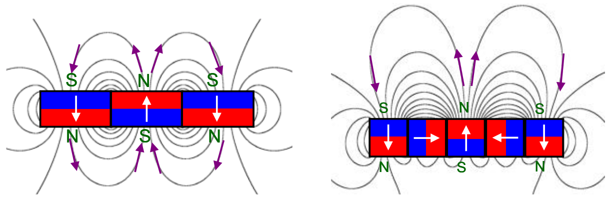

Figure 18. *Halbach array in the rectangular form [23]*

4. Conclusion

In conclusion, many facts are revealed from the reviewing of various sources and the experiments. One of them is the air gap affects the torque and rotational speed behaviour strongly. The other is MCs can transfer relatively less change of the torque even though there are a few misalignments. Also, an abrupt loading or fast starting-up of the rotation causes loss of the synchronisation. Moreover, a ratio between the magnet's angular width and the number of pole pairs, cannot be forgotten since it determines the transferable torque as well. It is found that a greater number of magnets does not mean stronger torque. Furthermore, power losses due to EC are quite huge especially at high speed and rises proportionally as the speed increases.

Considering the experimental results, they represent almost similar data as the other papers revealed which could be considered as successful. Such as the smaller air gap, the larger transferrable torque, fast starting-up can cause a failure in synchronising and abrupt loading breaks the rotation if the torque is not enough. The unconventional MC had reasons why they are not utilised because they do not transfer the torque well or smoothly.

In the end, the derived results, and the expectable difficulties, eight fundamental designing ideas for the HSMC are suggested. And they are focused on three factors mainly which are, mechanical deformation, the moment of inertia and temperature. These factors must be taken into consideration for designing the HSMC.

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Symbols

E_R rotational energy (J)
I moment of inertia (kg·m^2)
ω angular velocity (rad/s)
m mass (kg)
D outer diameter (m)
d inner diameter (m)

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