Impact of the Magnet Span on the Forces of Electrodynamic Suspensions with an Alternate Permanent Magnet Arrangement

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***Abstract*—Permanent magnet (PM) electrodynamic suspensions offer a simple and robust solution to assure the magnetic levitation of high-speed transportation systems. Halbach arrays (HAs), which are the PM magnetic field sources with the best performance, are more complex to implement than alternate poles configurations. Therefore, starting from a topology optimization, this paper studies the impact of geometrical parameters, and mainly the magnet span, on the alternate PM structure with the aim of improving its performance. It is shown that the lift-to-weight ratio can increase by 11% when changing the span of the permanent magnets for specific magnet dimensions, closing the difference with the Halbach array to only 2%. When considering the edge effects in 3-D, the alternate PM configuration even outperforms the HA. However, even though the span has also a positive impact on the lift-to-drag ratio, this last metric is not in the favour of the alternate PM arrangement.**

***Index Terms*—EDS, electrodynamic, suspension, permanent magnet, alternate.**

I. Introduction

MAGNETIC levitation enables transportation systems to reach very high speeds, by removing the mechanical frictions and vibrations [1]. From the interaction between a magnetic field source moving above a conductive track and the resulting eddy currents, electrodynamic suspensions (EDSs) produce electromagnetic forces able to levitate the vehicle. Permanent magnets (PMs) offer a simple and robust way to generate a magnetic field. Therefore, PM-EDSs have been deeply studied during the past years. The PMs are usually arranged in a Halbach array (HA) configuration [2], [3], due to a higher magnetic flux density in the track. However, building a large-scale HA can be more challenging than alternating magnetic poles attached to a ferromagnetic back-iron. Thus improving the performance of this arrangement can be helpful. A way to do so is to investigate new shapes and dimensions of the PMs. Although the geometrical parameters of the PMs may affect the forces but also the PM weight and thus their cost, no studies have been carried out on these parameters so far for an alternate PM arrangement, except briefly in [4].

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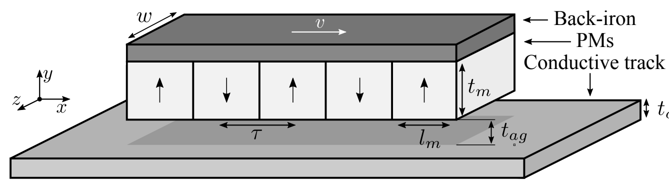

Fig. 1. PM-EDS structure.

Topology optimization of electrical machines has shown great results [5], [6] but was never applied to PM-EDS. In a fixed volume, this method can lead to an optimized geometry.

In this context, this paper investigates the influence of geometrical parameters of the PMs on the forces generated by PM-EDSs with alternating PMs. The goal is to improve the performance of this suspension system to be more competitive compared to the HA arrangement. Section II introduces the structure of the PM-EDS and defines the criteria. A topology optimization is carried out to extract geometrical features in Section III. Section IV studies then the impact of these features on the suspension. The optimized alternate PM and the HA configurations are finally compared in Section V.

II. Structure and Criteria

PM-EDSs are made of two parts: a moving magnetic field source made of PMs and a fixed conductive track. These two elements are depicted in Fig. 1. The interaction between the eddy currents induced in the conductive track and the magnetic field that produced them generates forces. The lift force, along the y-axis, levitates the vehicle whereas the drag force, along the x-axis, opposes to the displacement.

From this, two basic criteria are derived. The lift-to-weight ratio, noted LWR, is the ratio between the lift force and the weight of the PMs. The lift-to-drag ratio, noted LDR, is ratio between the lift and the drag forces. The LWR is linked to the PM material quantity whereas the LDR is linked to the efficiency of the suspension.

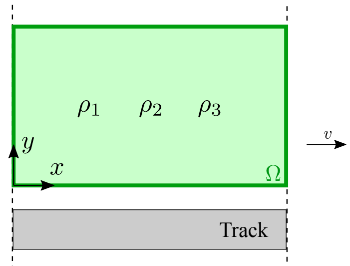

Fig. 2. The moving domain Ω on which the topology optimization is applied, highlighted in green. The dashed lines represents antiperiodic conditions.

TABLE I
PARAMETERS FOR THE TOPOLOGY OPTIMIZATION

Parameter	Symbol	Value	Unit
Translational speed	v	50	m/s
Pole pitch	τ	0.2	m
Air gap	t_{ag}	30	mm
Track thickness	t_c	15	mm
Track conductivity	σ_c	3.5e7	S
Back-iron permeability	$\mu_{r,Ir}$	2000	-
PM remanence	$B_{r,\text{PM}}$	1.4	T

III. Topology Optimization

The study starts from a topology optimization of the moving part of the PM-EDS. Within the design domain Ω in Fig. 2, three material densities ρ_1, ρ_2 and ρ_3 are defined. From these, the relative permeability and the remanence can be computed as:

$$\frac{1}{\mu_r} = 1 + \left(\frac{1}{\mu_{r,Ir}} - 1\right)\ \rho_1 \tag{1}$$

$$B_r = B_{r,\text{PM}}\ \rho_2 \tag{2}$$

where $\mu_{r,Ir}$ is the relative permeability of the ferromagnetic material and $B_{r,\text{PM}}$ is the remanence of the PM. The third density, indicating the presence of air, is computed from the two others as:

$$\rho_3 = 1 - \rho_1 - \rho_2 \tag{3}$$

The LWR is optimized with the fixed parameters detailed in Table I. In the resulting geometry depicted in Fig. 3, several features can be observed. First, the PM does not cover the whole pole pitch, inducing an air gap between the PMs. Then, the PM is more trapezoidal than rectangular with a curved shape at the top. Finally, the back-iron is not flat but carved on both sides.

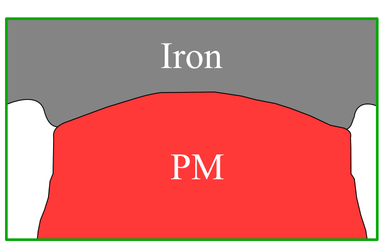

Fig. 3. Result of the topology optimization.

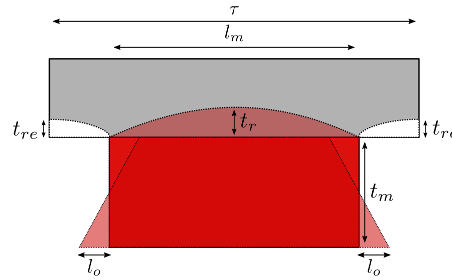

Fig. 4. Parameterization of the magnet shape following the topology optimization.

IV. Parametric Sweep

From the observations in Section III, we can parameterize the geometry to study the impact of each one of these features on the LWR. Fig. 4 shows this parameterization where l_m defines the average length of the PM and τ the pole pitch. The span factor can then be defined as:

$$\alpha = \frac{l_m}{\tau} \tag{4}$$

The sides of the PM can be inclined with a certain slope inducing an exceeding length l_o. The top part of the PM can be curved with a distance t_r between the top of the curved part, modeled as a portion of circle, and the horizontal. The holes in the back-iron are modeled as quarters of an ellipse with a short semi-axis equal to t_{re}.

As illustrated in Fig. 5, l_o and t_{re} appear to have a very low influence on the LWR with less than 1% of variation. The value found by the topology optimization for the third parameter t_r seems not to be optimal. This could be due to a difference between the parameterized geometry and the results of the topology optimization or to the thin zone between the PM and the iron with mixed materials. These three parameters are therefore classified as secondary parameters and simply considered as null in further discussions.

The resulting shape of the PM is thus a rectangle, parameterized by the pole pitch, the PM thickness, and the span factor. As shown in Fig. 6, these three parameters have indeed a significant impact on the LWR. With $\alpha = 0.8$, the LWR increases by 11% compared to the full span configuration with the same pole pitch and PM thickness.

V. Comparison with Halbach Array

The alternate PM and Halbach array configurations are represented in Fig. 7. Only three parameters are varied for their comparison: the pole pitch τ, the span factor α and the PM thickness t_m. As shown in Section IV, the span factor has a significant impact on the LWR and needs therefore to included in the comparison. Motivated by the work of Kublin *et al.* [7], a span factor is also considered for the HA, where it is defined as the ratio between the length of the vertically and horizontally magnetized PMs:

$$\alpha = \frac{l_{m,v}}{l_{m,h}} \tag{5}$$

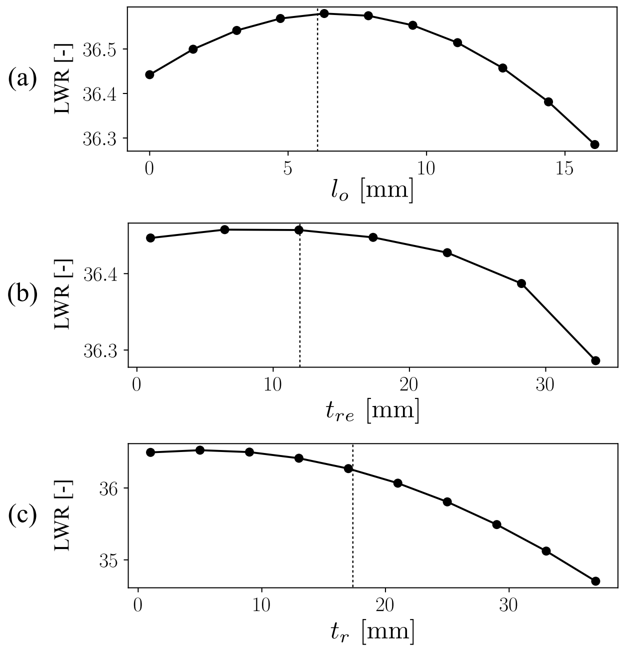

Fig. 5. Impact of secondary parameters on the LWR. (a) Exceeding side length. (b) Short semi-axis of the carved side ellipses. (c) Distance between the upper face of the PM and the horizontal. The dashed lines are the values extracted from the topology optimization.

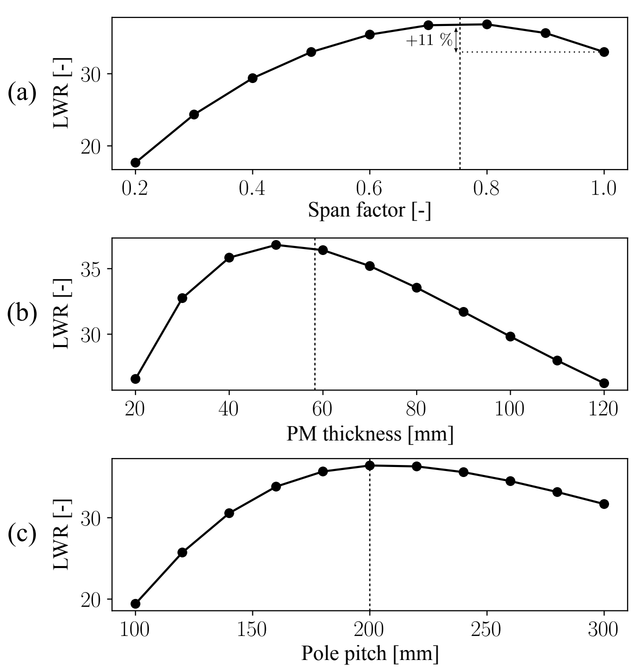

Fig. 6. Impact of the main parameters on the LWR. (a) Span factor. (b) PM thickness. (c) Pole pitch. The vertical dashed line is the value extracted from the topology optimization.

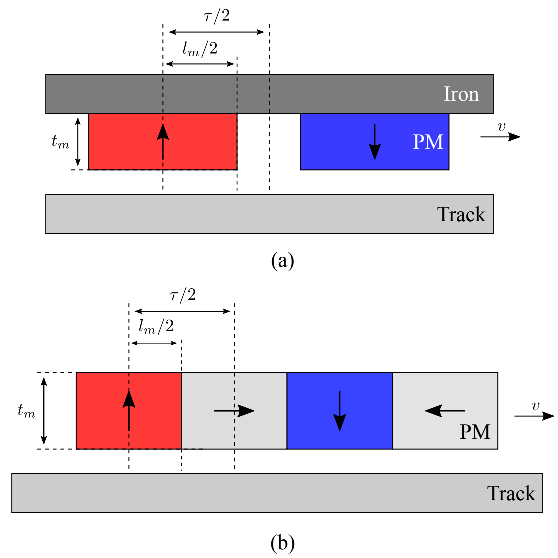

Fig. 7. PM arrangements and parameterization. (a) Alternate PM. (b) Halbach array.

TABLE II
OPTIMIZATION RESULTS

Parameter	Alt PM full span	Alt PM	HA
LWR [-]	33.2	37.1	37.8
t_m [mm]	46	45	81
τ [mm]	187	180	204
α [-]	1	0.76	0.5

For this comparison, the back-iron is not included in the LWR since it can be considered as a structural element of the suspension, which is also required for the HA where it does not have to be ferromagnetic.

An optimization of the LWR was carried out using COMSOL Multiphysics, leading to the results in Table II. The value of the LWR obtained with an alternate PM arrangement can come close to the one of the HA because of the magnet span. With a gain superior to 11% with an α equal to 0.76, the difference in LWR with the HA goes below 2%. It is interesting to observe that the PM thickness and the pole pitch maximizing the LWR of the HA are close to the analytical values found in [2], being $(4\pi/5\ t_{ag})$ and $(2\pi\ t_{ag})$ respectively. The ratio between the thickness of the PMs and the pole pitch is thus different from 0.5.

Because of practical constraints or because other criteria such as the LDR have to be considered, the design point can deviate from the optimum of the LWR. It is then interesting to assess the influence of the pole pitch and the PM thickness on the optimum span factor. To do so, the pole pitch and the PM thickness are varied around their optimal values, in the range [100 mm, 300 mm] and [20 mm, 120 mm] respectively. Among these points, five of them are selected in Fig. 8. Fig. 9 depicts the influence of the span factor for these five points. This reveals that the optimal span factor for both the HA and the alternate PM configurations is not affected by the dimensions. Only the α maximizing the LWR of alternate

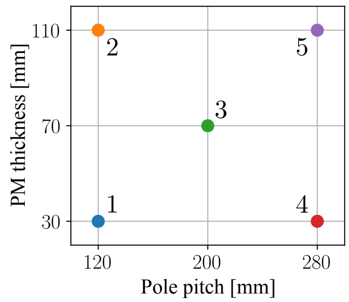

Fig. 8. Sampling of the parameter grid.

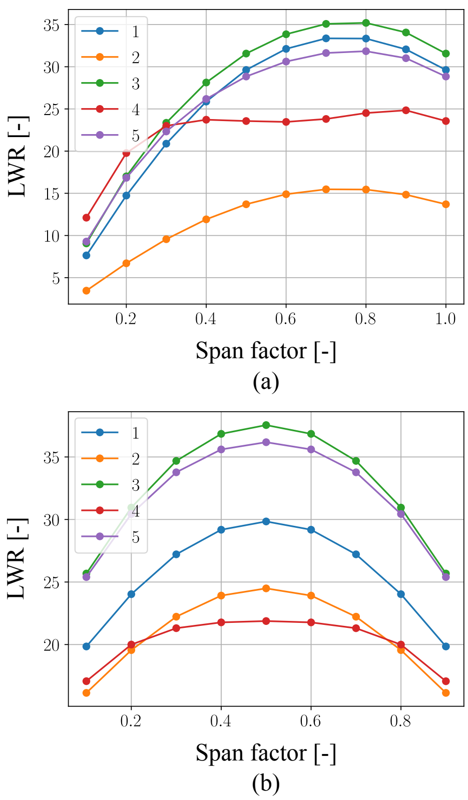

Fig. 9. Impact of the span factor on the LWR for 5 combinations of τ and t_m. (a) for the alternate PM. (b) for the HA.

PM for a large pole pitch and short PM thickness is slightly different. The behavior of the LWR of the HA with the span factor is symmetrical around 0.5 meaning that increasing the span of the vertically magnetized PM or the horizontally magnetized PM has the same effect, which is significantly different from the conclusion drawn in [7]. However, Kublin *et al.* did their study in 3-D where both the edge and end effects could have an impact on the eddy currents and explain the difference.

Knowing this, it is possible to study the impact of the pole pitch and the PM thickness with a fixed optimal span factor equal to 0.5 for the HA and 0.8 for the alternate PM configurations. Fig. 10 compares the LWR of both magnetic field sources as a function of the dimensions. In the considered

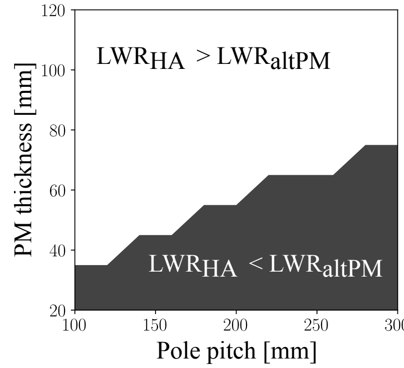

Fig. 10. Map of dimensions where the LWR of the alternate PM is greater than that of the HA with their respective optimal span factors.

range of τ and t_m, the LWR of the alternate PM is higher than that of the HA for an aspect ratio t_m/τ below a value around 0.3. Fig. 11 gives a more precise view of the impact of the dimensions on the LWR of each arrangement. The maximum values of the LWR given in Table II are visible in Fig. 11.

The alternate PM reaches its optimum for smaller dimensions. The transverse edge effects due to the finite width of the PMs increasing with the pole pitch [8], the alternate PM could therefore have, for a fixed PM width, a better LWR than the HA, at their optimal point. This phenomenon is visible in Fig. 12 where the LWR is computed in 3-D for both configurations as a function of the ratio between the width of PMs and the pole pitch w/τ at low speed. Even though the 2-D LWR of the HA is slightly higher, the 3-D LWR of the alternate PM is greater for a large scale of widths. When $w = 2\tau$, the LWR of the alternate PM is still 5% higher. It should be noted that an optimization in 3-D of the LWR could lead to other conclusions.

Besides the LWR, one can be interested in the LDR and the impact of the span and the configuration on this ratio. The LDR of both alternate PM and HA configurations is depicted in Fig. 13. The dimensions are kept the same as before since it is rather meaningless to optimize the LDR considering that LDR $\propto \sqrt{\tau}$ [3] and the PM thickness has a low influence on the LDR. However, for specific dimensions, there exists also an optimum span maximizing the LDR with a gain compared to the full span configuration. As for the LWR, this optimum does not depend on the pole pitch nor the PM thickness. For the dimensions around the optimum LWR, the point 3, the LDR increases by 1.5% whereas the gain is around 7.8% with the dimensions of the point 4. The alternate PM and HA have fairly the same LDR for the same dimensions. Since the LDR evolves with $\sqrt{\tau}$ and the pole pitch maximizing the LWR of the HA is longer, the HA can have a higher LDR for the same LWR.

VI. Conclusion

The alternate PM configuration in PM-EDSs can be easier to build than its Halbach array counterpart but at the cost of reduced performances. The article tried then to optimize

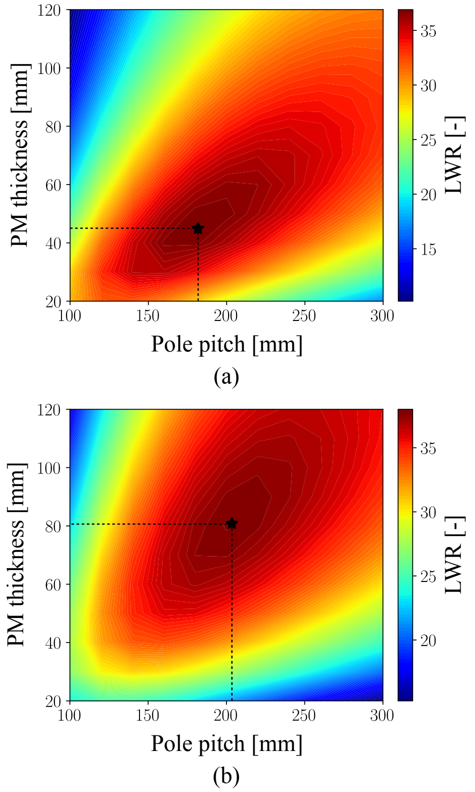

Fig. 11. Impact of the dimensions on the LWR with the optimal span factor. (a) for the alternate PM, $\alpha = 0.8$. (b) for the HA, $\alpha = 0.5$. The stars indicate the optimal points given in Table II.

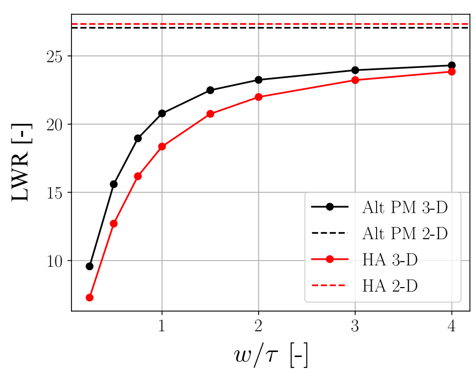

Fig. 12. Impact of the edge effects on the LWR of the alternate PM and HA configurations at 5 m/s with the dimensions of Table II.

this arrangement to reach similar levels of performance. A topology optimization showed that introducing an air gap between the PMs can enhance the LWR. With the span factor of the PM, defined as the ratio between the length of the PM and the pole pitch, equal to 0.76, the alternate PM can therefore have a difference below 2% compared to an optimized HA against 14% with the basic full span structure. Besides, this optimum factor does not depend much on the pole pitch nor the PM thickness. The alternate PM structure reaches its best LWR with smaller dimensions than the HA leading to a lower impact of the edge effects but also to a

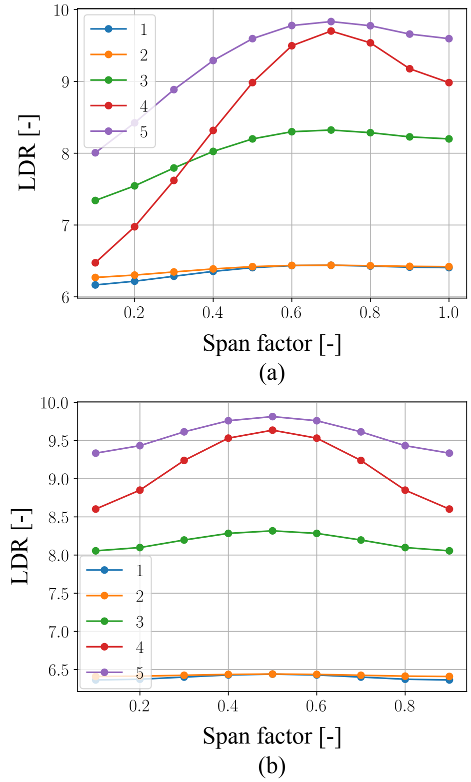

Fig. 13. Impact of the span factor on the LDR for 5 combinations of τ and t_m. (a) for the alternate PM. (b) for the HA.

lower LDR. Finally, the LDR can be improved as well by selecting a span factor around 0.7 but the gain is smaller and depends on the dimensions of the PMs.

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