Design of a Combined Passive and Active Magnetic Shield Adapted to Electrical Machines

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DESIGN OF A COMBINED PASSIVE AND ACTIVE MAGNETIC SHIELD ADAPTED TO ELECTRICAL MACHINES

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***Abstract*— The paper deals with a method that makes it possible to design a shielding adapted to a given device. The method uses a field harmonic representation to identify the magneto dynamic multipoles associated to the studied device. This representation classifies the sources with respect to their main features: their amplitude, their associated decreasing law, their frequency nature. Then, depending on the required magnetic level, the classification indicates the multipoles to be suppressed. At this point, three possibilities are offered with the use of a passive, active or combined shielding. Each kind of shielding presents advantages and drawbacks. Each of them has a particular effect on a given magneto dynamic multipole. As a consequence, it is possible to design the more adapted shielding with respect to magnetic specifications. A simple but didactic example using an electrical motor illustrates the method and the different shielding strategies.**

I. INTRODUCTION

Controlling the stray fields generated by electrical devices is a specification met in many applications to ensure the best efficiency of a global system. Regarding military ships that include more and more electrical equipments, it is a crucial point to focus on: besides a question of electromagnetic compatibility between components, great attention must be paid to magnetic silence and stray fields created outside the ship.

Even if some tools [1] and rules [2] have already been developed to take into account magnetic stray field reduction at first steps of conception, in a practical way, electrical equipment is chosen or designed on the only bases of required electro mechanical performances. The question of the generated magnetic stray field level comes generally in a second time. If it is necessary to reduce the stray fields, the problem is then shifted towards how to design an adapted shielding system.

The paper deals with an original and powerful method dedicated to shield design.

The first step of the method consists in finding the equivalent multipoles associated to a device by using harmonic decomposition of the magnetic field. This identification is a dynamic generalization of the classical static one [3], [4].

In a second time, two shielding strategies are investigated.

The first approach uses conductive and/or magnetic properties of materials to attenuate the stray fields. The second way to reduce stray field is to add conductors around the device. If both principles of shielding are quite well known, their application generally lies on experience, and no rational method is available to size them. By applying boundary conditions on previous harmonic decomposition, a fast and analytical tool of passive and active shield design is created: it is then easy to determine how the shielding parameters can influence and reduce each dynamic mutipole associated to the source. Thus, a rational tool is obtained to rationally size shields [5].

Finally, this original approach is illustrated by the study of an electrical motor shield design. To be didactic, harmonic decomposition and development about passive and active shields are presented in 2D. Different cases are simulated with a finite element software. It shows how simple and powerful the method is.

II. DESIGN METHOD

A. MagnetoDynamic Identification (MDI)

The method uses the decomposition of the magnetic field in harmonics (polar harmonics in 2D and spherical harmonics in 3D). This decomposition is the general solution for the Laplace equation in the chosen coordinate reference. In the 2D polar reference, it is written as:

$$\vec{B}(r,\theta) = \left| \begin{array}{l} -\sum_{n=1}^{\infty} C_n . r^{-(n+1)} . \sin(n\theta + \phi_n) \\ \frac{C_0}{r} + \sum_{n=1}^{\infty} C_n . r^{-(n+1)} . \cos(n\theta + \phi_n) \end{array} \right. \quad (1)$$

The above static expression already shows how the equivalent multipoles [6] associated to the source are naturally classified: one term of given order n presents its amplitude Cn, its specific periodicity and its own decreasing law as $1/r^{n+1}$. This last property means that at a chosen distance far from the source center, the infinite series becomes a finite series with maximum order N. Besides, term periodicity implies that a static identification must verify Shannon sampling condition to be correct.

As an electrical device generally presents frequency varying sources, a dynamic generalization for the previous expression must be found.

In the air and for low frequencies, if $\vec{B}$ is a magneto static solution, $\vec{B}.f(t)$ is a magneto dynamic solution (where f(t) is a given function of time) of Laplace equation. Three types of sources can be distinguished : the pulsating, the rotating and both pulsating and rotating ones. Their relative expressions are:

$$\vec{B}_p(r,\theta,t) = \left| \begin{array}{l} -\sum_{n=1}^{\infty} C_{n,\omega}.r^{-(n+1)}.\sin(n\theta+\phi_n).\sin(\omega t+\xi) \\ \left\{ \frac{C_0}{r} + \sum_{n=1}^{\infty} C_{n,\omega}.r^{-(n+1)}.\cos(n\theta+\phi_n) \right\}.\sin(\omega t+\xi) \end{array} \right. \quad (2)$$

$$\vec{B}_r(r,\theta,t) = \left| \begin{array}{l} \sum_{n=1}^{\infty} C_{n,\Omega}.r^{-(n+1)}.\sin(n\Omega t-n\theta-\phi_n) \\ \sum_{n=1}^{\infty} C_{n,\Omega}.r^{-(n+1)}.\cos(n\Omega t-n\theta-\phi_n) \end{array} \right. \quad (3)$$

$$\vec{B}_{rp}(r,\theta,t) = \left| \begin{array}{l} \sum_{n=1}^{\infty} C_{n,\Omega,\omega}.r^{-(n+1)}.\sin(n\Omega t-n\theta-\phi_n).\sin(\omega t+\xi) \\ \sum_{n=1}^{\infty} C_{n,\Omega,\omega}.r^{-(n+1)}.\cos(n\Omega t-n\theta-\phi_n).\sin(\omega t+\xi) \end{array} \right. \quad (4)$$

The MagnetoDynamic Identification makes it possible to determine the orders, amplitudes and dynamic natures of the multipoles associated to a given source, this source being any combination of the three above expressions.

The necessary conditions for a correct MDI is to have enough sensors around the device and an adapted time sampling to verify spatial and time Shannon Theorem respectively.

Then, in a first step, a frequency extraction is made on all the sensors. The induction corresponding to each main frequency is represented on a time-space diagram whose shape is clearly linked to its dynamic nature (pulsating or rotating).

In a second time, a spatial FFT is applied to the time-space diagram to identify the associated orders.

As a consequence, based on a magnetodynamic generalization of the static harmonic decomposition, the MDI proposes the identification and the classification of the equivalent multipoles associated to a device. They can be classified according to interesting features: their amplitude, their decreasing law and their dynamic nature (pulsating or rotating). With respect to given specifications, it is then easy to determine which term must be decreased to reduce stray field.

It appears clearly that the MDI, being both space and time Fourier Transformation at the same time, gives far more information than a simple FFT on a sensor.

B. Shield design

Let us assume now that the magnetic stray field created by a source is known, for example once it has been identified by the MDI. How a shielding system will influence the equivalent multipolar model?

1) Passive shielding

To answer the question in the case of a passive shield, the problem described on Figure 1 must be solved: how harmonic terms due to the source (Σ) are changed in (C) by the presence of magnetic and/or conductive media in (B)?

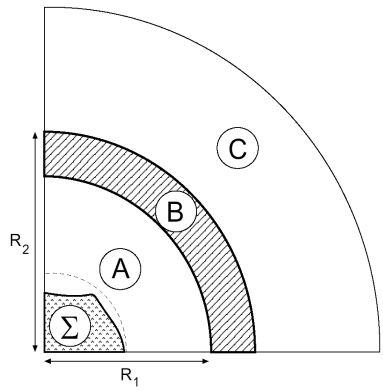

Fig.1. Description of a standard shielding problem: zones (A) and (C) are made of air and zone (B) of magnetic and/or conductive material; (Σ) is the device to shield.

For simple shape of the shield, analytical expressions of induction in (C) can be found. They are obtained by applying limit conditions on internal and external surfaces of the shield.

Previous expressions were magnetodynamic solutions of the field in a non conductive media (air) outside the device. To write limit conditions, solution is also required inside conductive media. Thus, the problem to solve corresponds to the diffusion equation (displacement currents are negligible for frequencies lower than 1kHz). In 2D polar coordinates and with a complex notation, the induction has a classical general expression [7] using the Bessel functions of the second kind and their derivates:

$$\vec{B} = \left| \begin{array}{l} -\sum_{n=0}^{\infty} \frac{n}{r}\left[C'_n K_n((1+j)\frac{r}{\delta}) + D'_n I_n((1+j)\frac{r}{\delta}) \right] \sin(n\theta+\varphi_n)e^{j\omega t} \\ -\sum_{n=0}^{\infty} \left[C'_n K^{(1)}{}_n((1+j)\frac{r}{\delta}) + D'_n I^{(1)}{}_n((1+j)\frac{r}{\delta}) \right] \cos(n\theta+\varphi_n)e^{j\omega t} \end{array} \right. \quad (5)$$

With: $\delta = \sqrt{\frac{2}{\sigma\mu\omega}}$, skin depth (m)

μ: magnetic permeability of the media (Tm/A)

σ : conductivity of the media $(Sm)^{-1}$

I_n: Bessel function of the second kind

K_n: Bessel function of the second kind

$$I^{(1)}{}_n = \frac{(1+j)}{\delta}\frac{\partial I_n}{\partial r}$$

$$K^{(1)}{}_n = \frac{(1+j)}{\delta}\frac{\partial K_n}{\partial r}$$

The boundary conditions between the different zones lead to a linear equation system. This system directly links the field harmonic terms of the source and outside the field via an attenuation coefficient.

To illustrate the magnetodynamic attenuation two examples of shield are presented: the first one is made of aluminium and the other one is made of steel. This representation applied to the two magnetic shields highlights two different comportments relative to the two types of material (Fig.2 and Fig.3).

The static values of the attenuation appear on the two representation when f=0Hz. In the aluminium shielding case (Fig.2) the magnetic shield is inefficient for a static source and attenuation coefficient is always equal to 1. Another point clearly appears: for a given frequency the shielding attenuation is stronger for the lower order.

When the magnetic shield is made of steel, the static attenuation (f=0Hz) is the departure point of the dynamic attenuation. The more efficient the magnetostatic shield is the more efficient it will be for a dynamic source. Nevertheless, for magnetic and conducting shield a maximum of the attenuation exist at fixed frequency. This maximum is placed where the eddy current and magnetic attenuation are equal.

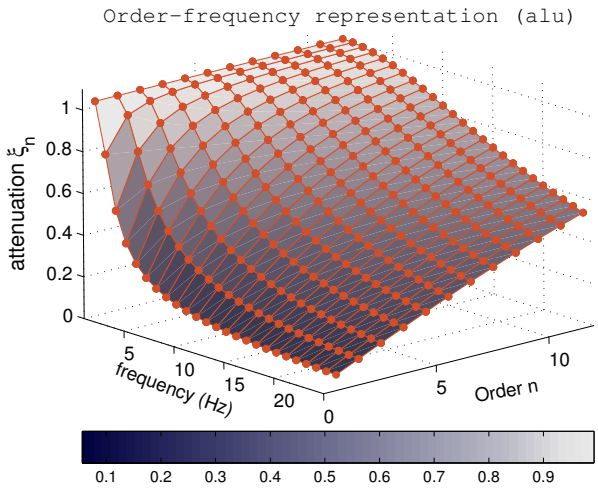

Fig.2. Attenuation with respect to order and frequency for an aluminium shield of internal radius 600mm and a depth of 10mm.

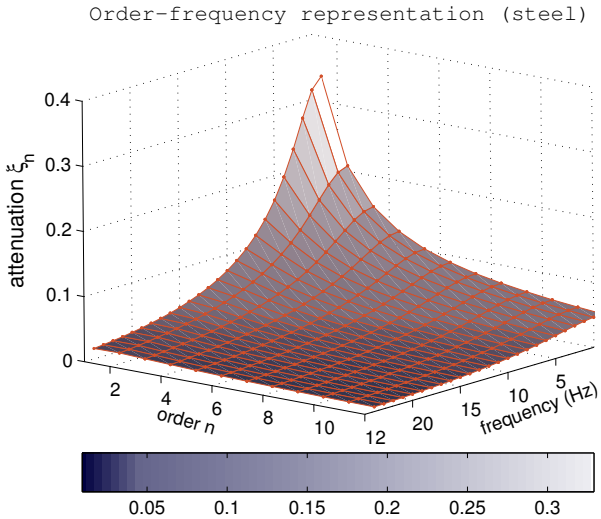

Fig.3. Attenuation with respect to order and frequency for a shield made of steel, whose internal radius is 600mm and depth is10mm.

2) Active shielding

Another way to make a magnetic shield is to set conductors with appropriated currents all around the source. This method can delete (and not attenuate) the magnetic induction due to a term of the harmonic expansion of the source, but one or several current sources are required.

To determine the currents in the active shield, the surface current density that creates the same magnetic field as the identified source must be used. The following boundary condition determines the value of this current density on the surface between two areas A and B:

$$\begin{cases} \left[\vec{n}\times(\vec{B}_B(P)-\vec{B}_A(P))\right]=\mu_0\vec{K}(P) \\ \left[\vec{n}\cdot(\vec{B}_B(P)-\vec{B}_A(P))\right]=0 \end{cases} \quad (5)$$

In polar coordinates, at each point P of the active shield, the current density distribution K creating the induction (2) can be written as:

$$\vec{K}(r,\theta,t)=\left[\frac{C_0}{r}+\sum_{n=1}^{\infty}\left[2C_n r^{-(n+1)}\right]\cos(n\theta+\varphi_n)\right]e^{j\varpi t}\vec{e}_z \quad (6)$$

Moreover, if the conductors are set around a circle whose radius is R_0 (Figure 4), it is possible to calculate the equivalent currents to K as:

$$K(R_0,\theta,t)=\frac{\Delta I(R_0,\theta,t)}{R_0\cdot\Delta\theta} \quad (7)$$

And the current amplitude in each conductor to delete the magnetic induction due to the source (Σ) is:

$$I_k(R_0,t)=-\frac{1}{\mu_0}\cdot\left[C_0\beta+\sum_{n=1}^{\infty}\left[2\beta C_n R_0^{-n}\right]\cos(n\alpha_k+\varphi_n)\right]e^{j\omega t} \quad (8)$$

The last but essential point is the minimum number of conductors that creates specific harmonic term without any additive noisy terms. As a consequence, it is necessary

to study the harmonic decomposition of the active shield to create the purest harmonic terms.

The active shield main interest is its possibility to create exactly one or several harmonic terms whatever their orders are.

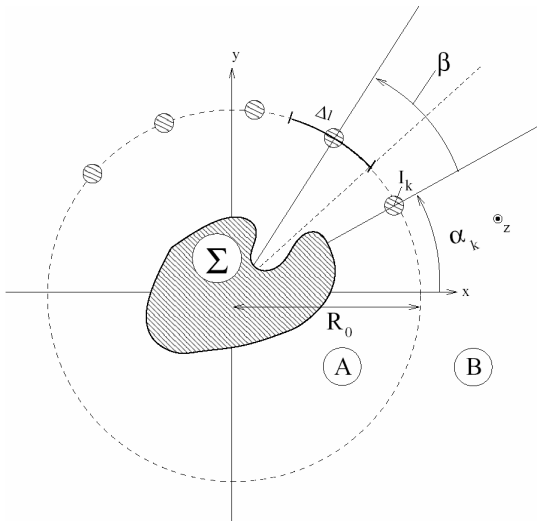

Fig.4. Position of conductors of an active shielding;
Conductors are defined to reduce or suppress in zone (B) harmonic term of field created by the device (Σ)

III. A DIDACTICAL EXAMPLE

Naval propulsion motor commonly develops high power (a few MW). To ensure magnetic safety, it is crucial to predict which stray field level they generate and how the signature can be controlled. On a magnetic stray field point of view, a motor also presents one of the more complex sources on board: fields rotate inside the airgap, currents pulsate or are constant while rotating, magnets can turn, eddy currents are developed in iron housing. For these reasons, illustration of our method is chosen for a motor.

A. MDI of a motor and stray field specifications

The studied motor is not a propulsion motor: it is a given motor, with given geometry, magnetic properties and windings. Nevertheless, to be as realistic as possible, its electromagnetic characteristics are chosen to be roughly the same as a propulsion motor.

In more details, the motor is a synchronous permanent magnet motor with radial flux. It has 27 teeth and 24 poles, for an external radius of 52cm. Its rotation speed is low (100rpm), which corresponds to low frequency for stator currents (20Hz). It is studied under load operation.

Its signature is determined by 2D finite element modeling (Figure 5).

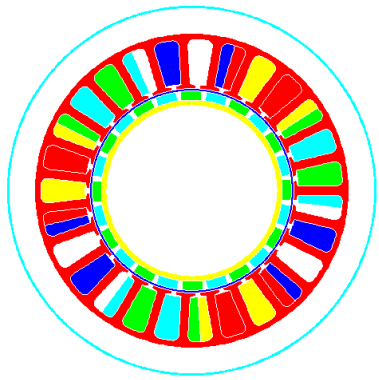

Fig.5. modeled motor (24 poles, 27 teeth, external radius of 52cm)

The MDI applied to the loaded motor (Table 1 for r = 65cm) highlights that the 2 main frequencies are the supply current frequency (20Hz) and its third harmonics (60Hz). The signature at current frequency contains many different orders: 3, 6, 12 and 15. Orders 3 and 6 are linked to the stator currents, orders 12 and 15 to rotor magnets (order 15 is due to tooth effect). These terms are significant close to the motor (at 13cm far from it). Further, for example at a distance equivalent to one motor diameter, the lowest orders remain, because of their slower decreasing law: order 3 is then predominant with a 470nT amplitude (Table 2 for r = 120cm).

If now the magnetic stray field specifications require a induction level lower than 50nT at 120cm far from the motor for any frequency between 5 and 20Hz, which shielding should we use?

Sources	S1	S2	S3	S4	S5
FFT frequency (Hz)	20	20	20	20	60
$f_{rot} = \Omega/2\pi$ (Hz)	6,67	-3,33	1,67	-1,33	6,67
$f_{pul} = \omega/2\pi$ (Hz)	0	0	0	0	0
Order n	3	6	12	15	9
Cn (T)	5.10^{-6}	4.10^{-6}	$8,2.10^{-6}$	$3,41.10^{-6}$	$0,6.10^{-6}$

Table 1. MDI applied to the loaded motor rotating at 100rpm, close to the motor (r =65cm)

Sources	S1	S2	S3	S4	S5
FFT frequency (Hz)	20	20	20	20	60
$f_{rot} = \Omega/2\pi$ (Hz)	6,67	-3,33	1,67	-1,33	6,67
$f_{pul} = \omega/2\pi$ (Hz)	0	0	0	0	0
Order n	3	6	12	15	9
Cn (nT)	310	50	---	---	---

Table 2. MDI applied to the loaded motor rotating at 100rpm, far from the motor (r =120cm)

B. *Passive shield sizing (ideal case)*

With respect to specifications, the attenuation coefficient must be 10% for an order 3 at 20Hz. Let us choose an internal shield radius of 60cm.

A 10mm thick shield made of aluminium would attenuate the signature of 18% at nominal speed (a 18mm thick shield gives rigorously 10%, see Figure 6). But as aluminium is not magnetic, its attenuation coefficient is close to one for very low frequency. On the contrary, for the same geometry, steel ensures that the signature remains low for speed variations.

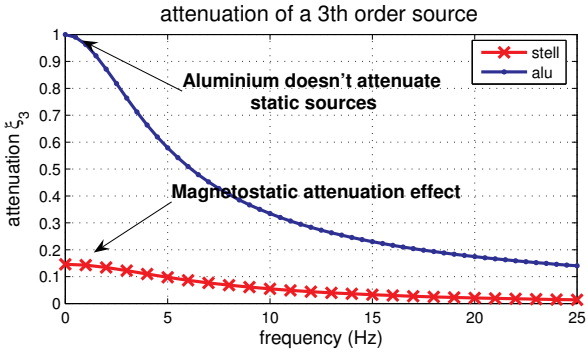

Fig.6. Frequency variations of attenuation coefficient for order 3 and 2 kinds of material (60cm internal shield radius and 1cm thickness)

To test our approach, the defined shield is added around the machine. At 20hz, the main field term (order 3) is attenuated in the expected proportion (Table 3) : around 2%.

Sources	S1	S2
FFT frequency (Hz)	20	20
$f_{rot} = \Omega/2\pi$ (Hz)	6,67	-3,33
$f_{pul} = \omega/2\pi$ (Hz)	0	0
Order n	3	6
Cn (nT)	7,5	0,8

Table 3. MDI applied to the loaded motor rotating at 100rpm, far from the motor (r =120cm), with a steel shield of 1cm thickness.

C. *Passive shield efficiency in practice*

Our finite element model gives an ideal magnetic image of the motor. It assumes that our motor has zero internal fault: no rotor eccentricity, no stator current unbalance, perfect periodicity, etc. The reality is different and very often, a geometrical or magnetic break in symmetry generates specific order terms at given frequencies.

For example, let us assume that one rotor magnet presents a lower magnetization (90% of the others). A simple FFT on only one sensor shows that low frequencies appear, clearly linked to the faulty rotor magnet (Figure 7).

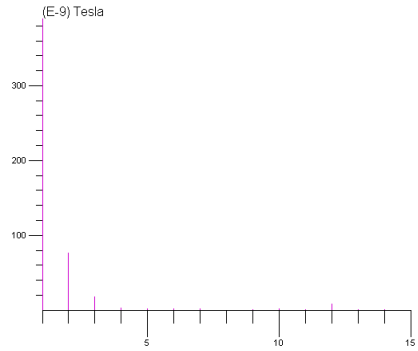

Fig.7. FFT on the measured induction (harmonic one corresponds to rotation frequency) on one sensor, for faulty rotor magnet case (with passive shield)

The MDI gives further information about the faulty magnet: each low frequency (first harmonics of rotation speed) is associated to one pure order (Table 4).In this case, the passive shield is no more efficient. It can not face two difficulties: the first one is that an even small rotor unbalance provokes a quite high signature; the second point is that a first order at low rotation speed is created. This term would require at least a 5% attenuation coefficient to meet specifications whereas the shield only provides 35%.

Sources	S'1	S'2	S'3	S'4	S1	S2
FFT frequency (Hz)	1,67	3,33	5	6,66	20	20
$f_{rot} = \Omega/2\pi$ (Hz)	1,67	1,67	1,67	1,67	6,67	-3,33
$f_{pul} = \omega/2\pi$ (Hz)	0	0	0	0	0	0
Order n	1	2	3	4	3	6
Cn (nT)	395	82	19	6	7,4	0,8

Table 4. MDI applied to the loaded motor rotating at 100rpm, far from the motor (r =120cm), with a steel shield of 1cm thickness and one faulty rotor magnet

To properly attenuate this term, a larger shield should have been chosen: 2,7cm at nominal speed and 4,6cm at a quarter of nominal speed, instead of 1cm. This means a high increase of volume and weight. Another strategy would be to combine active and passive shielding: minimum thickness of magnetic material for high order-frequency terms and additive conductors to reduce specifically these low order-frequency terms

IV. ACTIVE SHIELD DEDICATED TO LOW ORDER-FREQUENCY TERMS

Six conductors are set inside previous shield to generate a rotating first order field at rotation speed. The advantage to put the active shield inside the passive one is

that higher harmonics due to current density distribution into conductors are naturally filtered.

Thanks to these additive currents, first order term is eliminated (Figure 8). On the same way, second order could also have been suppressed.

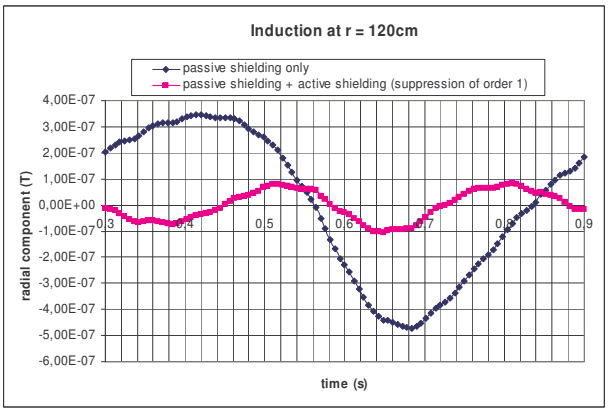

Fig. 8. Suppression of first order term thanks to active shield (loaded motor rotating at 100rpm with one faulty rotor magnet)

V. CONCLUSION

As a conclusion, thanks to harmonic expansion of field, an original tool has been developed that gives a rational electromagnetic shield sizing of any electrical device. The shield can be active and/or passive. Its application to an electrical motor show how powerful the method is. More than an illustration, it also presents the general problematic of the magnetic stray field created by a motor and how to well model and control them.

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