Suppression of structural force harmonics by controller in PM bearingless motor

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Abstract
In permanent magnet (PM) bearingless motors some design characteristics can create ripples on force during the rotation depending on the levitation current and the rotational speed. This paper proposes a method to eliminate these ripples by the injection of additional current harmonics. This current is injected by a special structure of control taking into account the interaction highlighted by the theatrical analysis of the force ripples. This control method is validated by experimental results.

Keywords: bearingless motor, PM motor, force ripples, force harmonics compensation, control, experimental validation.

1. Introduction
In recent years, several researches on bearingless motor showed the impact of motor design on the ripple of levitation forces. in order to avoid the excitation of proper frequencies, reducing or eliminating the force ripples is needed. To reduce these forces ripples, some authors propose special topology chosen for their pole pair number (Schneider and Petersen, 2008), coil pitch (Jin and Bingnan, 2014) or adapted magnetization of the rotor magnets (Lapôtre and Takorabet, 2015). Moreover, some solutions implemented in active magnetic bearings to eliminate synchronous perturbations by an active control have been proposed (Herzog and Buhler, 1996).
This paper proposes to adapt the magnetic bearings solutions for the bearingless motor by taking into account the effect of the motor currents to increase the control reactivity.

2. Theory
The radial forces in bearingless motor are expressed along the two axes x and y in (Lapôtre and Takorabet, 2015), the forces are the sum of elementary forces according to flux density distribution harmonics. These forces are expressed in complex form as sum of the complex elementary forces:

$$F = \sum_{s,\sigma,i} F_{i,s,\sigma} \tag{1}$$

with

$$F_{i,s,\sigma} = K_{i,s,\sigma}\, e^{i(\theta_{n,s,i}-\theta_{n,\sigma,i+1})} \tag{2}$$

Where $K_{i,s,\sigma}$ is a factor depending on the flux density harmonic of rank i generated by the source s (current or magnet), the flux density harmonic of rank $i+1$ generated by the source σ and geometric parameters of the machine.

Referring to (Lapôtre and Takorabet, 2015), the coefficient $K_{i,s,\sigma}$ is expressed as the product of two coefficients according to the flux density source:

$$K_{i,s,\sigma} = C_{i,s}.C'_{i+1,\sigma} \quad (3)$$

In this equation, the norm of the force harmonics $K_{i,s,\sigma}$ is directly proportional to the flux density sources. This relationship is represented in coefficients $C_{i,s}$ and $C_{i,\sigma}$. when the considered source (s or σ) is a magnet, the coefficient $C_{i,s}$ or $C'_{i+1,\sigma}$ is constant. In the case that the considered source (s or σ) is a current, $C_{i,s}$ or $C'_{i+1,\sigma}$ is proportional to the norm of the source current due to Ampere's theory:

$$C_{i,s} = d_{i,s} I_s \quad (4)$$

where $d_{i,s}$ is the constant coefficient and I_s is the norm of the source current.

In the following parts, a bearingless 6-phase PM motor having a 1 pole pair rotor magnet with radial magnetization is considered. The stator current vector generates two current distributions of one pole pair ($\overline{I_{dq}}$ for torque generation) and two pole pairs ($\overline{I_{xy}}$ for levitation force generation). The 2nd and 4th harmonics of the levitation force are due to the magnet and the levitation current ($\overline{I_{xy}}$) as can be shown in (Lapôtre and Takorabet, 2015). Taking into account equations (2), (3) and (4), the expression of the force harmonics of ranks 2 and 4 which is used in the next section are:

$$\begin{cases} F_{2,I_{xy},magnet} = d_{2,xy} I_{xy} e^{i\left(\omega t+\varphi_{2,I_{xy}}\right)} C'_{3,magnet} e^{i(-3\omega t+\varphi_{3,magnet})} \\ F_{4,magnet,I_{xy}} = C_{3,magnet} e^{i(3\omega t+\varphi_{3,magnet})} d'_{4,xy} I_{xy} e^{i\left(\omega t+\varphi_{4,I_{xy}}\right)} \end{cases} \quad (5)$$

Where I_{xy}, is the norm of the levitation current $\overline{I_{xy}}$. $\varphi_{2,I_{xy}}$, $\varphi_{4,I_{xy}}$, are the phases of flux density harmonics of ranks 2 and 4 generated by the levitation current $\overline{I_{xy}}$. $\varphi_{3,magnet}$ is the phase of flux density 3rd harmonic generated by the magnet. $d_{2,xy}$, $C'_{3,magnet}$, $C_{3,magnet}$, $d'_{4,I_{xy}}$ are constant related to the design of the machine.

3. Control

We choose to start with a classical control scheme presented in (Chiba,2005). To compensate by an active control each force harmonic, this control scheme is modified to remove the considered force harmonic. A new control method, as shown in Figure 1 and 2, is proposed. Indeed, each force harmonic generates a displacement of the same frequency. This property is used to characterize the force harmonics. For evaluating this harmonic of displacement, a rotation matrix is used and the other harmonics are eliminated by a low pass filter. This displacement evaluation is then used as an input to a PI controller and the results are transformed in complex form to be multiplied by the levitation current in complex form to obtain the same formulation of equation (4). Contrary to classical solutions, this control method eliminates synchronous perturbations at the 2nd or 4th harmonic function of the levitation currant $\overline{I_{xy}}$. The compensating terms being functions of $\overline{I_{xy}}$, in case of change of the levitation force ($\overline{I_{xy}}$ variation) the proposed control scheme allows to suppress the transient time of the controllers. The new reference currant is obtained by summation of the outputs of the classical levitation controller and the 2 compensating terms for each force harmonic which should be cancelled (Fig 1 and 2).

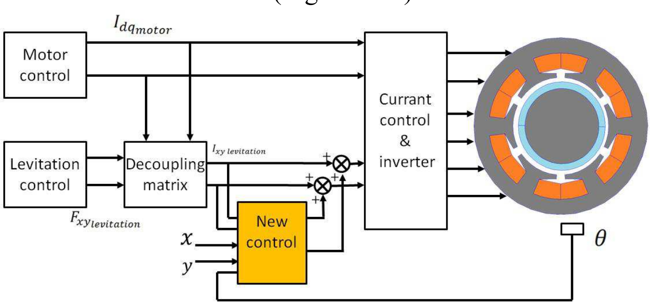

Fig. 1 Control of bearingless motor

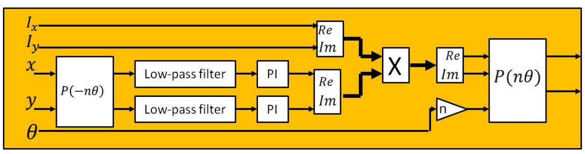

Fig. 2 New control

4. Experimental results

To test this control method, a prototype has been set up and shown in Fig. 3. This prototype has two active magnetic bearings and one bearingless motor with 6 wounded stator teeth and a one pole pair rotor magnet with radial magnetization. First, to characterize the bearingless motor, the levitation are realized by the two active magnetic bearings. Then, the levitation is performed with one active magnetic bearing and the bearingless motor, so the second active magnetic bearing can be used to generate controlled perturbations. Knowing that the force harmonics are naturally filtered at high speed, the different tests are realized at low speed, *e.g.* 50 *rad*/*s*, to show the effectiveness of the new control method.

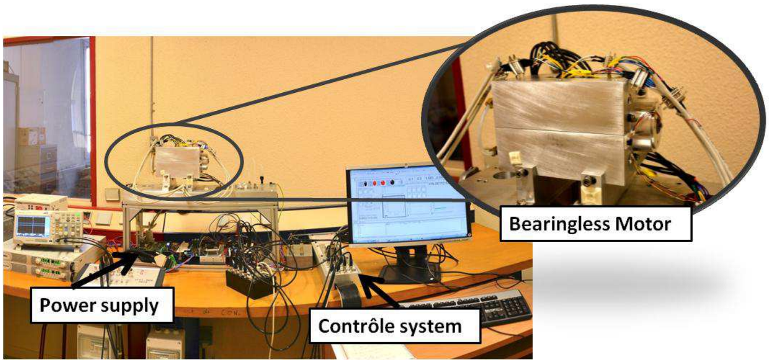

Fig. 3 Experimental test-bench at GREEN.

To observe the different force harmonics, using the active magnetic bearings we measure the force generated by bearingless motor when a constant force reference is impose by the classical control scheme. The measured x and y force components are shown in Fig. 4. The spectral decomposition of these force components given in Fig. 5 shows the different ranks of force harmonics and their level. The most important force harmonic is the 4th one, followed by the 2nd one as predicted. The most important harmonic has a norm of 25% of the constant force. This analysis illustrates the importance to take into account these aspects.

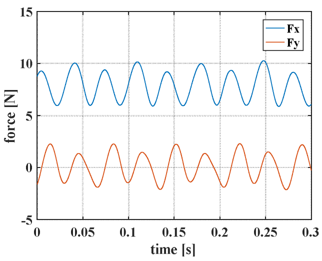

Fig. 4 force generate by constant levitation currant I_x

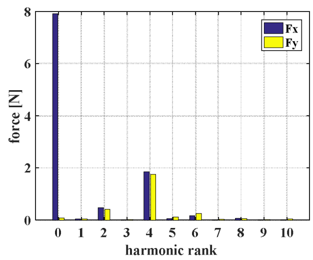

Fig. 5: spectral decomposition of force of Fig4

In order to test and visualize the effect of the propose control, the new control method is applied to cancel the force harmonics of ranks 2 and 4. The first test is performed under the same conditions but with the new control method. The rotor center positions *x* and *y* are stabilized in this test, so the inputs of new control bloc (Fig. 2) are replaced by the force components F_x and F_y measured by the active magnetic bearings. Fig. 6 shows the results for a constant current levitation . In this case the force ripples are significantly reduced. For different values of the levitation current, Fig. 7 shows the spectral decomposition of the force component F_x. this figure highlights the effectiveness of the proposed control for suppressing the force harmonics. It can be noticed that the PI controller output variations are less than 5% on the whole test.

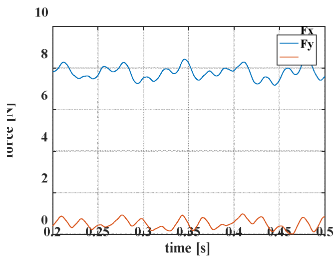

Fig. 6: force create by constant currant I_x with new control

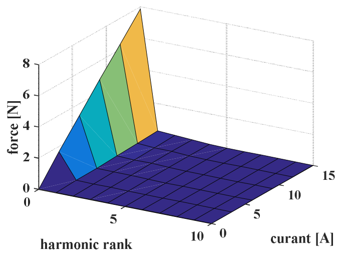

Fig. 7: spectral decomposition of F_x function of I_x

A test with a levitation generated with one active magnetic bearing and the bearingless is performed with classical control scheme at low speed in order to show the generated harmonics as shown in Fig. 8. Then, turning on the new control method allows eliminating harmonics 2 and 4 as shown in Fig. 9. This figure shows the effectiveness of the new control method. The perturbation due to the force harmonics of rank 2 and 4 is suppressed successfully and corresponding displacements are eliminating.

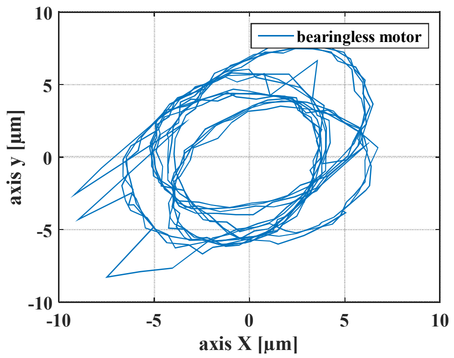

Fig. 8 orbital position without suppression of force harmonics

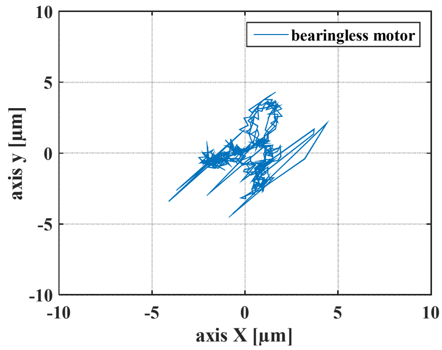

Fig. 9. orbital position with suppression of force harmonic of ranks 2 and 4

This new control method creates a harmonic component, directly proportional to the speed, on the current reference. The bandwidth of the current control loop might introduce a delay between the action of injected currents and the measured perturbation at higher speeds. This is the main limitation of the proposed control method.

6. Conclusion

In this paper, an improved control is proposed to eliminate the force harmonics generated by the topology of bearingless PM motors. The new control method is tested on a laboratory prototype and the obtained results show its effectiveness on eliminating the force ripples. Thanks to this control method, multiple unconsidered topologies due to their important force ripples level may be envisaged.

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