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Design of Magnetic Actuator for Rotating Machinery Analysis

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Abstract: A magnetic actuator as excitation source in rotating systems is proposed to introduce an external excitation force without contact. Although the use of electromagnets for applying forces to rotating machinery have been carried out with high performance level (for example, magnetic bearings), the development of a conveniently easy and cheap device for laboratory application presents interesting contribution to experimental methods used in test rigs based on similarity design to rotating machinery. The initial concept of the magnetic actuator proposed here is simple, but enables either the external excitation without contact or the vibration control when associated with a controller system. However, the evaluation of performance characteristics to attend the dynamic demand of the system in not so trivial. The paper brings considerations on electromechanical model used, the influence on the coil distribution, electric current applied to the coils, the air-gap between actuator and rotating shaft, the type of surface of the actuator poles (flat or round) as well as excitation frequency.

Keywords: excitation without contact, rotordynamics, magnetic actuator.

NOMENCLATURE

A = cross section area, m^2
B = magnetic flux density, Wb/m^2
F =force, N
fc = cut-off frequency, Hz
g =air-gap length, m
H = magnetic field intensity, A/m
I =moment of inertia, kg.m^2
i =current, A
K =stiffness, N/m
L = indutance, H
l = length, m
P =magnetic permeance , Wb/A
M = mass of the system, kg
N =number of coils
R =resistance, Ω
Q =charged particles
U =voltage, V
W =energy, J
x =displacement, m

Greek Symbols

μ = permeability coefficient, Tm/A
Φ =magnetic flux, Wb
Θ =magnetic motive force, A
$\Re$ =magnetic reluctivity, A/Wb
λ = linked flux, Wb
ω =frequency, rad/s
θ =angle, rad

Subscripts

a relative to particle a
b relative to particle b
c relative to magnetic material
f relative to magnetic energy
g relative to air gap
m relative to magnetic force
me relative to mechanical energy

INTRODUCTION

The reality of the design area, concerning mechanic and mechatronic systems, demands clearly the importance of keeping constant advances in development and improvement of structures, and consequently, accurate analysis and tests more representative and rigorous, pointing out the evident importance of determining dynamics properties of such structures, mainly: natural frequencies, damping factors and vibration mode shapes, among others. To proceed with an experimental analysis, an external excitation force necessarily must be applied to the structure, being usually obtained from electromechanic exciters, named shakers. The application of the electromechanic exciter demands a mechanical connection between this device and the structure (flexible stick, technically named stinger). Once the connection is done, the exciter can be controlled by a signal generator, capable of introducing different kinds of signals to the structure. The connection between exciter and structure, as well as the kind of signal generated, represent parameters with expressive importance concerning the quality of results to be obtained during the tests.

In rotordynamics, there is a lack in experimental part, involving modal analysis in rotating machinery, which is precisely the application of an external excitation force without contact, one of the several factors which can be able to minimize the excessive signal noise problem when acquired in high rotational speeds. The noise influence occurs in part due to the journal/bearing friction, as noticed previously in experiments with shaker application.

In this context, the electromagnetic actuator appears as a possible proposal to solve this question, being the main focus of this work, once these devices enable the external excitation by electromagnetic force, without any kind of mechanical contact. Such forces are generated by permanent magnets or controlled electromagnets.

The application of magnetic actuators in engineering is significantly growing in importance, due to the advances in research and developments of controlled systems (Hsiao and Lee, 1994; Klesen, Nordmann and Schönhoff, 1999; Klesen and Nordmann, 1999), as well due to the application of metallic alloys, which offer best performance in magnetic circuits. Howe (2000) demonstrated several applications of magnetic actuators, highlightening the following areas: aerospace, automotive, industrial process, computational, monitoring and control, fault diagnosis and detection, as well as hospital equipment (Silani and Lovera, 2005; Lovera e Astolfi, 2004; Demierre et. Al., 2002; Aenis and Nordamnn, 1999 and 2002; Siegwart, R., Traxler, A., 1997).

Therefore, this work describes in the application of magnetic actuators in the mechanical systems excitation, as a contribution to what seems to configure the future of research and development in this subject (Pasquale, 2003; Garnier,2000; Christensen and Santos, 2005). Ji (2003) accomplished studies with a Jeffcott rotor supported by electromagnetic bearings, investigating time delay effects in the non-linear dynamic behavior, while Jang (2005) used active magnetic bearings with a sliding mode controller concept for flexible rotors.

To improve the knowledge about the influence of some design parameters of the magnetic actuator in the dynamic response of structures, and further on, of rotordynamic response, an effect analysis of each parameter is proposed, applied to a stationary mechanical system. Furthermore, the estimation of electromagnetic forces is carried out by measuring the magnetic field and the electric current applied to the system, since the modal analysis of the system by using a magnetic actuator requires essentially the excitation force control (Castro et Al., 2006).

ELECTROMAGNETIC CONCEPTS

Static Analysis

Magnetic Field Lines

A magnetic field can be represented by means of field lines, where the tangent to the line, at any point, gives the direction of the field at that point, while the distance among lines gives the field magnitude.

The motion of the electric charge creates a magnetic field. To a long conductor crossed by an electric current, a magnetic field is generated around it, as shown in Fig. 1.

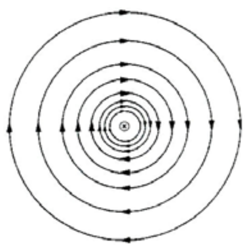


Figure 1 – Magnetic field lines to a current i crossing a long conductor.

The symbol ⊗ means that the current is directed inside the page.

Magnetic Field Evaluation

The Ampere Law gives the mathematical relation between the current distribution and the magnetic field:

$$\oint \vec{H}.d\vec{l} = \sum i \quad \rightarrow \quad \oint H\cos(\theta)dl = \sum i \tag{1}$$

The Ampere Law is applied on a closed amperian curve. The magnetic field intensity is given by H, dl is the differential line segment and i is the liquid current involved by the curve. The resultant current i is obtained by the algebraic sum of the currents crossing the amperian curve.

The magnetic field intensity H creates a magnetic field B in any circumstance and condition, through a characteristic factor, the permeability coefficient μ. The air permeability coefficient value is nearly $4\pi \times 10^{-7}$ (henry/meter).

$$B = \mu H \tag{2}$$

Solenoid

A filament rolled up as a helicoidal coil and crossed by an electric current defines a solenoid, which enables the application of the Ampere Law, when considered ideal, to evaluate the magnitude of the resultant magnetic field. Figure 2 shows the magnetic field lines for a solenoid (Halliday, 1996).

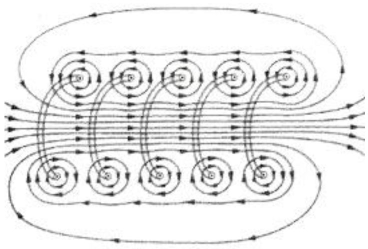


Figure 2 – Magnetic field lines in the cross-section of the solenoid axis center.

Which allows the application of the Ampere Law for a square amperian curve (involving the top and the center of the solenoid) given by Eq. (3);

$$\oint \vec{H}.d\vec{l} = \sum i \quad \rightarrow \quad Hl = Ni \tag{3}$$

where l is the length of the square side, N is the number of coils in the Amperian curve and i is the current crossing the coils.

Magnetic Force

Considering the system in Fig. (3) composed by an immovable part, which is involved by N spiral coils, and a movable part connected to a spring. Applying a potential difference in both ends of the coils, an electric current appears in the coils, generating a certain intensity of magnetic field H around each coil. Applying the Ampere Law for this circuit, Eq. (4) is obtained:

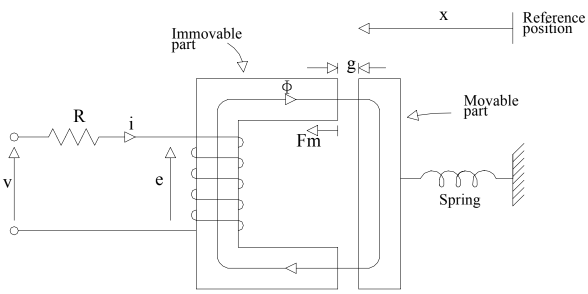


Figure 3 – Example of a electromecanical system.

$$Ni = H_c l_c + H_g l_g \tag{4}$$

where Ni is the magnetic motive force, $H_c l_c$ are the magnetic field intensity and length due magnetic material, $H_g l_g$ are the magnetic field intensity and length due air gap. The magnetic flux ϕ (weber) in the magnetic circuit is given by Eq.(5), defining A the cross-section area of the magnetic material, initially considered equal to the air gap area, and B the magnetic field.

$$\phi = AB \tag{5}$$

Assuming the same magnetic flux for both regions, of a linear system, equations (2) and (4) give:

$$Ni = B\left(\frac{l_c}{\mu_c} + \frac{l_g}{\mu_g}\right) \tag{6}$$

Considering the air gap permeability like the vacuum permeability $\mu_g \approx \mu_0 = 4\pi\times10^{-7}$, with the vacuum permeability smaller than magnetic material permeability $\mu_0 << \mu_c$, and $2g$ the air gap length, the magnetic field B can be obtained by:

$$B = \frac{\mu_0 Ni}{2g} \tag{7}$$

In this case, the energy stored in the magnetic fields is given by Eq. (8), (Sen,1997):

$$\begin{aligned} W_f &= \frac{B^2}{2\mu_0}\times \text{volume of air gap} \\ &= \frac{B^2}{2\mu_0}\times 2Ag \end{aligned} \tag{8}$$

Taking into account the mechanical energy W_m equal to the energy stored in the magnetic field W_f, an infinitesimal displacement dx results in a infinitesimal variation dW_m in the mechanical energy. So, when Ni is constant:

$$\begin{aligned} f_m dx &= dW_m = -dW_f \\ f_m &= -\frac{dW_f(x)}{dx} \end{aligned} \tag{9}$$

The negative value of the force means it acts towards diminishing the air gap. Substituting Eq. (8) and (9):

$$\begin{aligned} f_m &= \frac{d}{dg}\left(\frac{B^2}{2\mu_0}\times A\times 2g\right) \\ f_m &= \frac{AB^2}{\mu_0} \end{aligned} \tag{10}$$

Equation (10) enables the evaluation of the magnetic force f_m through the magnetic field B.

Dynamic Behavior of Coil

The current in the coil is described by Eq. (11) in time domain;

$$U(t) = L\frac{dI(t)}{dt} + RI(t) \tag{11}$$

Where U is the applied Voltage; L is the inductance and R is the resistance of the coil.

In the frequency domain there is:

$$\begin{aligned} U(j\omega) &= (Lj\omega + R)I(j\omega), \textbf{or} \\ I(j\omega) &= \frac{\frac{1}{R}}{\frac{L}{R}j\omega + 1}U(j\omega) \end{aligned} \tag{12}$$

For a constant RL-combination the current in the coils and, therefore the actuator force will decrease with the frequency increasing of the voltage signal applied to the coil. The cut-off frequency f_c is:

$$f_c = \frac{R}{2\pi L} \tag{13}$$

A power Amplifier that delivers high voltages in combination with a current or a flux density controller is a useful approach to raise the cut-off frequency.

RESULTS

As the main objective of this work is to investigate the influence of input parameters (current, air-gap, frequency) on the magnetic force, a Finite Element Model has been created for it. A Flux® program was applied for simulate a simple core with one and two coils. To close the magnetic circuit a ferromagnetic journal was simulated too. The journal is a simple cylinder with 80mm of length and 40mm of diameter. The dimensions of the core are in millimeters in Fig. (4).

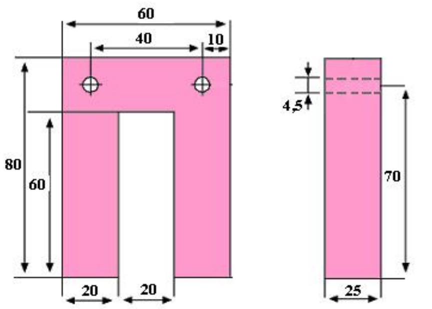
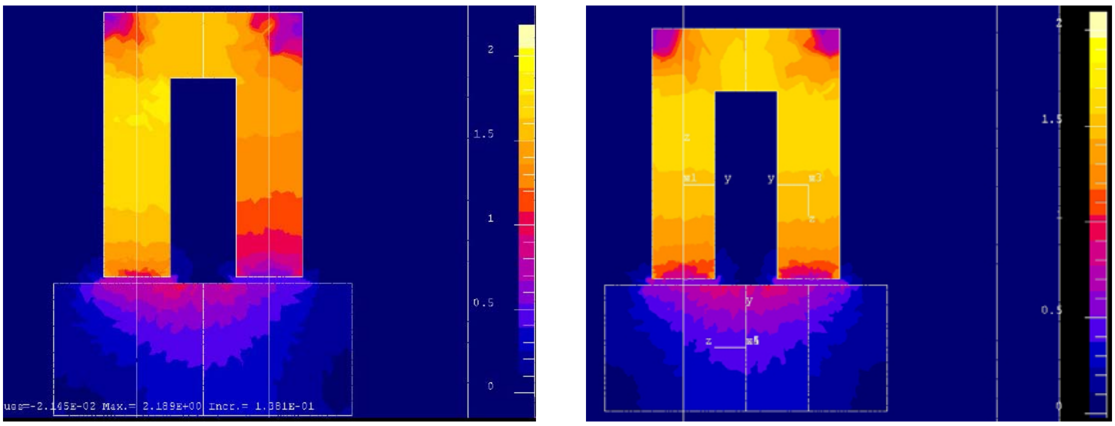


Figure 4 – Actuator dimensions in millimeters.

Number of Coils

Even so Eq. (10) gives the relation between the magnetic field (B) and the magnetic force (f_m) on the system and Eq. (7) shows how to calculate the magnetic field from actuator parameters, both does not show the influence of the coils distribution on the resultant magnetic force. Two different kinds of coils distribution were studied and its results are showed in Fig. (5).



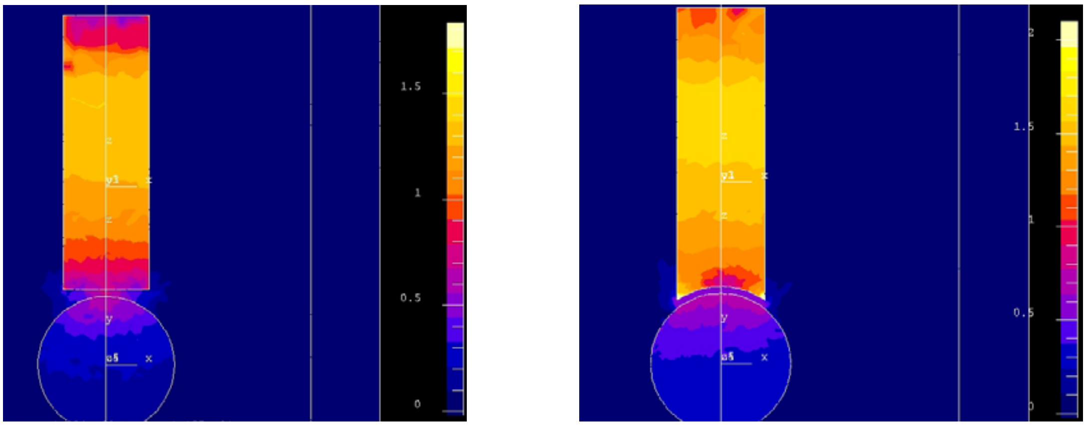
(a) **(b)**

Figure 5 – Coils distribution on the actuator: (a) One coil and (b) two coils.

Figure (5a) shows the magnetic field, with the unit in Tesla (T), on the magnetic actuator with just one coil. The bright color represent the higher magnetic field and the dark one the lower. As can be noticed on the left side of the core the magnetic field is higher than on the right side. This occurs because of the coil assembly. Also in the journal the magnetic field is non symmetrical. Figure (5b) shows the magnetic field distribution on the actuator with two coils. In this case each coil has a half number of turns when compared with that in Fig.(5a). The symmetrical magnetic field can be noticed in both regions, magnetic actuator and journal. It is an important characteristic for the magnetic force estimation.

Surface Shape Effect

Regarding the surface of the actuator poles, it can present a flat or a round shape. A flat pole surface (Fig. (6a)) can be adapted to various shaft diameters, but it leads to difficulties in the force evaluation because of the non constant air gap. The flux density distribution across the round pole air gap is practically constant but, in this case, the pole shape has to be defined to each shaft diameter (Fig. (6b)).

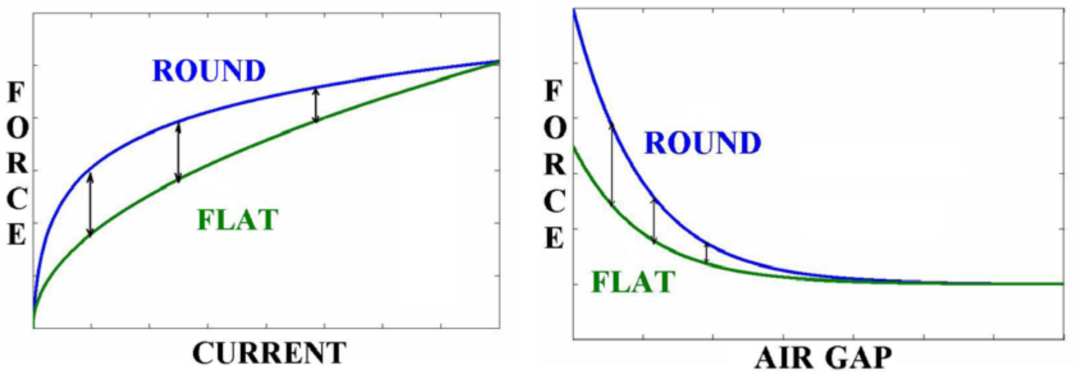


(a) (b)

Figure 6 – Effect of flat (a) and round (b) surface.

A round surface shown in Fig. (6b) has the advantage that the air gap is constant in the cross section, which is easier to handle for the force evaluation. The uniform magnetic flux in the air gap is important to calculate the actuator force using Eq.(10).

The difference between the magnetic force obtained from flat (green) and round (blue) surface will decrease with increase of magneto motive force (*Ni*). As the number of turns (*N*) in the coil remain constant, this effect can be visualized with of the current increasing, as in Fig.(7a). Further, if the magneto motive force (*Ni*) remains constant, the difference between the forces of both surfaces will decrease with the increasing of the air gap, as shows Fig.(7b).



(a) (b)

Figure 7 – Current (a) and air gap (b) influence on the magnetic force for flat and round surface.

Actuator Model

The magnetic actuator is a mechatronic system. In this way, its behavior depends directly on the subsystems that makes part of it. With a proposal of studying the magnetic behavior requested for the dynamical movement, a model with the main subsystems which constitute the magnetic actuator was developed. The main devices considered are the type of excitation, the signal amplifier, the electric circuit (Coils), the magnetic force and the mechanical system with 1 degree of freedom. Figure (8) shows the complete model of the actuator subsystems represented in small blocks. Table (1) presents the values of the parameters used in simulation results, with units in SI.

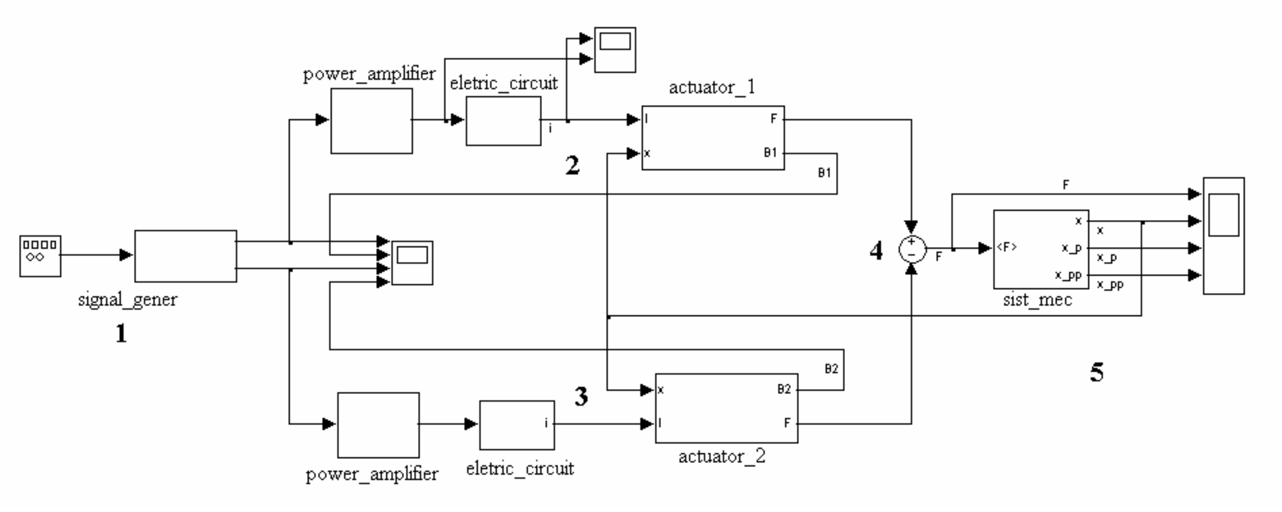


Figure 8 – Actuator system model.

The model was based on the system presented in Fig. (9). The numbers in Fig (8) represents the modeled regions. The first region is the signal generation which has two output channels. The second represents the power amplifier, the RL circuit of the coil and the force obtained from Eq. (10), which represent one actuator. Number three is the same model previously used for the opposite actuator. The resultant force is obtained in region number four. And the resultant force is applied on mechanical system represented by 1 d.o.f. in region number five.

Table 1 – Parameters used in the model.

Mechanical system	Electrical system (Coils)	Actuator
Mass = 1,25 (Kg) Damping = 10,5 (Nm/s) Stiffness = 3 x 10^5 (N/m)	Inductance = 3,13 x 10^{-3} (H) Resistance = 0,15 (Ω)	Area = 0,4 x 10^{-3} (m^2) Turns = 280 μ_0 = 4π x 10^{-7} (Tm/A) Air gap = 1,25 x 10^{-3} (m)

As the main objective is to use the magnetic actuator to excite rotating systems and reminding the actuator supplies only attractive force, two opposite actuators are necessary to excite such system in one direction, constituting a pair of actuators. Figure (9) represents the pair of actuators where the resultant force is the sum of the forces by each actuator.

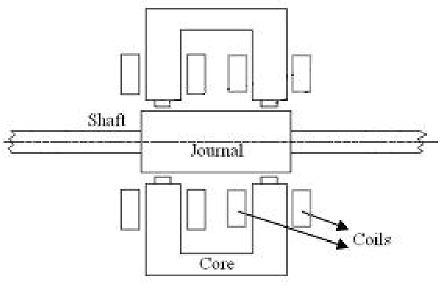
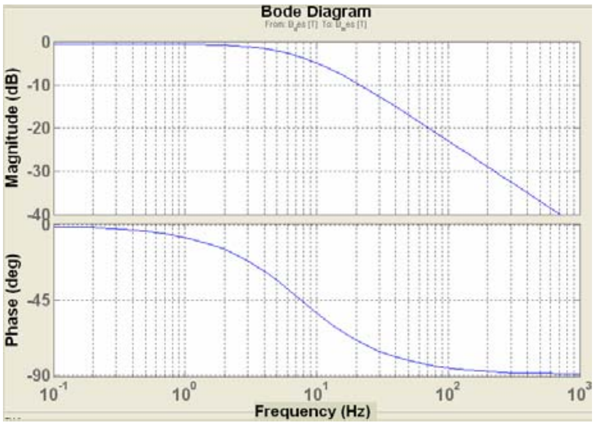
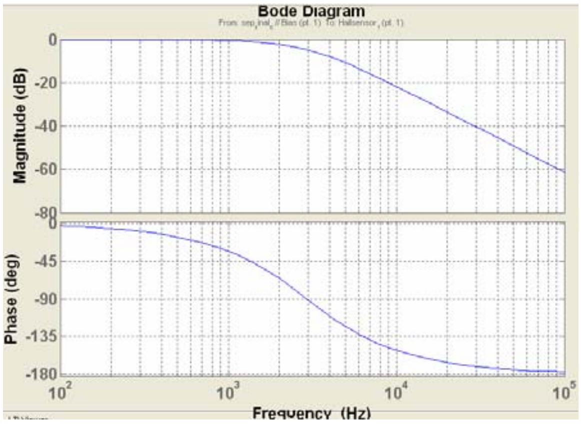


Figure 9 – Opposite actuators: a push-pull arrangement.

The control on amplitude and frequency of the excitation force are characteristics desired for the magnetic actuator, because many types of signals can be used in the modal analysis. The use of hall sensors enables to measure the magnetic field and then to calculate the applied force (Eq. (10)), but the control on the frequency depends on the system response. From Eq. (12), it is possible to observe the first order behavior of the coils, where the cut-off frequency is shows in Eq. (13). Thus, for the simulated results with the parameters listed in Table 1, the cut-off frequency is f_c=7,6(Hz). Figure (10) shows the bode diagram between desired magnetic field (B_des) and real magnetic field (B_mes) for the system without control (a), and the system with control (b).



(a)



(b)

Figure 10 – Bode diagram between desired magnetic field (B_des) and real magnetic field (B_mes) for the system without control (a), and the system with control (b).

Figure (11) shows the response for a sinusoidal excitation of 30Hz to reach a magnetic force of 50N, which corresponds approximately to a magnetic field of 0,4T. The first graphic shows the actuator force, the second graphic represents the necessary magnetic field to get the force magnitude and the third one shows the real magnetic field on the actuator. Both the desired magnetic field (B_des) and real magnetic field (B_mes) are related to one of the actuators, but the graphic of the force represents the resultant force by the actuator.

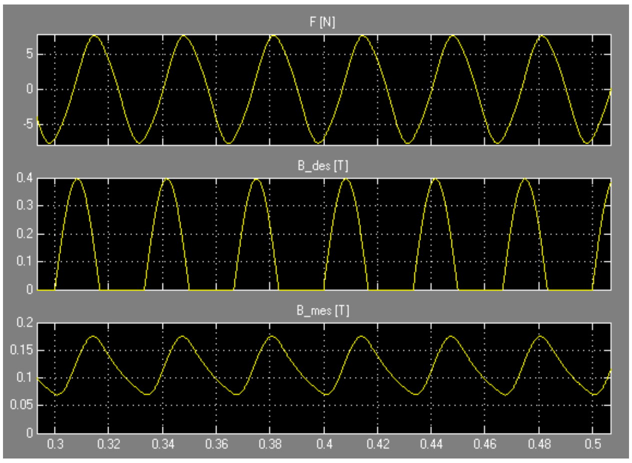


Figure 11 – Actuator force response for sinusoidal excitation. (a) Force response; (b) desired magnetic field and (c) obtained magnetic field.

As it can be noticed in Fig (11) the force is approximately 8 (N), very far from the magnitude of 50 (N). That is highlighted in the desired magnetic field of 0,4 (T) and the real obtained value of 0,17 (T). An useful way to solve this problem is a controller application.

The field actually generated by the actuator can be controlled, being able to reach the desired force for a specific frequency of excitation. A proportional controller was implemented in the simulated model to make a real magnetic field (B_mes) similar to the desired magnetic field (B_des). Figure (12) shows the response for the same type of excitation used in Fig.(11), however with the implemented controller.

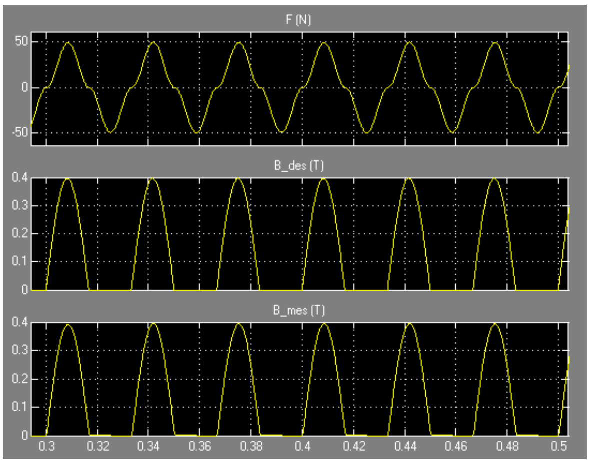


Figure 12 – Actuator force response with magnetic field control for sinusoidal excitation. (a) Force response; (b) desiderate magnetic field and (c) obtained magnetic field.

Figure (12) shows that the control allows to reach the desired force of 50N. This fact is pointed out when comparing the simulated magnetic field desired (B_des = 0,4 T) and the real magnetic field (B_mes = 0,4T). Using this type of controller, the limitation on the amplitude and the frequency of the excitation force depends on the amplifier.

However, as previously said, the excitation signal should be harmonic, what is not verified in the signal shape of the resultant force. The relation between force and magnetic field is given by Eq.(10). It gives the force dependency on the square of the magnetic field, what explains the shape of the force signal in Fig.(12).

In order to adjust the shape of the resultant signal to the actual excitation, a linear system is necessary, which does not happen in Eq.(10). Although Maslen (1999) shown the possibility of linearization of the system around a band of application with the use of a bias linearization. For example, for a sine excitation with maximum value of 0,4T a DC (Bias) of 0,2T and a peak to peak sine signal with value of 0,2T should be applied. Thus the final value will vary between 0 and 0,4T. The same procedure must be applied for the actuator in the opposite side however with a sine phase shifted of 180º (Maslen, 1999). Figure (13) presents the response of the system with controller and Bias linearization. It is clearly noticed that both signals present harmonic shapes.

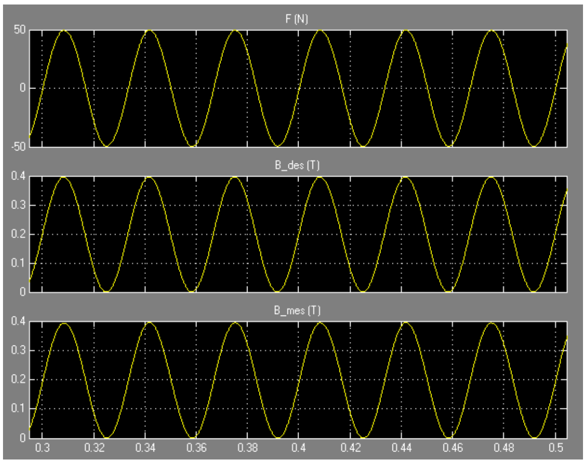


Figure 13 – Actuator force response with magnetic field control and Bias current for sinusoidal excitation. (a) Force response; (b) desiderate magnetic field and (c) obtained magnetic field.

The force amplitude (50 N) as well as the shape of the signal were obtained in the resultant force, leading to the viability of using control and Bias linearization to apply the magnetic actuator to excite dynamic systems.

CONCLUSION

The main focus of the paper is to investigate the design of a low-cost free-contact magnetic actuator to excite a rotordynamic system for the purpose of modal analysis. A Finite Element model was developed and the influence of parameters as coils distribution, pole surface shape, air gap and current on the magnetic force has been studied.

With two coils the symmetrical magnetic field could be observed in both regions, magnetic actuator and journal and this is an important characteristic for the magnetic force estimation. For a flat pole surface the magnetic field was not constant in the air gap but it is more flexible regarding to different shaft diameters. The round pole surface makes the magnetic field distribution across the air gap practically constant, however it is valid just for a specific shaft diameter. The F.E model shows that if the current or the air gap increase, the difference between the force obtained from flat or round surface decreases.

In the actuator model analysis, the force behavior, the importance of the magnetic field control and Bias current, were pointed out to obtain the desired amplitude and frequency excitation. The magnetic field control adjusted the force amplitude but not the signal shape. With magnetic field control and Bias current both force amplitude and signal shape were satisfactory obtained.

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REFERENCES

Aenis, M., 2002, “Einsatz aktiver Magnetlager zur modellbasierten Fehlerdiagnose in einer Kreiselpumpe“ – Dissertation, Technische Universität Darmstadt, Shaker Verlag, Aachen.

Aenis, M., Nordmann, R., 1999, “A Precise Force Measurement in Magnetic Bearing for Diagnostic Purpose” – 5th International Symposium on Magnetic Suspension Technology, Santa Barbara, USA.

Castro H.F., Furtado R.M., Cavalca K.L., Pederiva R., Butzek N., Nordmann R., “Experimental performance evaluation of magnetic actuator used in rotating machinery analysis”, JBSMSE – Journal of the Brazilian Society of Mechanical Sciences and Engineering, São Paulo, Brazil, pp.1-10, 2006.

Christensen, R. H., Santos, I.F., 2005, “Control of Rotor-Blade Coupled Vibrations Using Shaft-Based Actuation”, Proceedings of the XI DINAME, Ouro Petro, Brasil, pp. 1-9.

Demierre, M., Pesenti, S., Frounchi, J., Besse, P.A.,Popović, 2002, “Reference magnetic actuator for self-calibration of a very small sensor array”, Sensor and Actuator A Vol. 97-98, pp. 39-46.

Garnier, A., Bououina, T., Fujita, H., Hiramoto, T., Orsier, E., Peuzin, J.-C., 2000, “Magnetic Actuation of Bending and Torsional Vibrations for 2D optical-scannner application”, Sensors and Actuator A, Vol. 84, pp. 156-160.

Halliday, D., Resnick, R., Walker J., 1996. “Fundamentos de Física 3”. 4ª ed. Rio de Janeiro: LTC-Livros Técnicos e Científicos Editora S.A., 350p.

Howe, D., 2000, “Magnetic Actuators”, Sensor and Actuators A., Vol. 81, pp. 268-274.

Hsiao, F.-Z., Lee, A.-C., 1994, “An Investigation of the Characteristics of Eletromagnetic Bearing Using the Finite Element Method.”, Transaction of the ASME, Vol. 116.

Jang, M. J., Chen, C.L., Tsao, Y. M., 2005, “Sliding mode control for active magnetic bearing system with flexible rotor”, Journal of Franklin Institute, Vol. 342, pp. 401-419.

Ji, J. C., 2003, “Dynamics of a Jeffcott rotor-magnetic bearing system with time delays”, Non-linear Mechanics, Vol 38, pp. 1387-1401.

Klessen, C., Nordmann, R., Schönhoff, U., 1999, “Design of a Minimum Current Magnetic Bearing” – 5th International Symposium on Magnetic Suspension Technology, Santa Barbara, USA.

Klessen, C., Nordmann, R., 1999, “Entwicklung kostengünstiger Magnetlager.“ – Antriebstechnik, Zeitschrift für Konstruktion, Entwicklung und Anwendung von Antrieben und Steuerungen.

Lovera, M., Astolfi, A., 2004, “Spacecraft Attitude Control Using Magnetc Actuators”, Automatica, Vol. 40, pp. 1405-1414.

Maslen, E., Magnetic Bearings, University of Virginia, Department of Mechanical, Aerospace and Nuclear Engineering, Charlottesville, Virginia, 1999, 233 p.

Pasquale, M., 2003, “Mechanical Sensors and Actuators”, Sensors and Actuators A, Vol 106, pp. 142-148.

Sen, P. C., 1997, “Principles of Electric Machines and Power Electronics.” 2nd ed.John Wiley & Sons, 615 p.

Siegwart, R., Traxler, A., 1997, “Active Magnetic Bearings. Basics and Applications.” Update 5.97 special. – Winterthur: MECOS Traxler AG.

Silani, E., Lovera, M., 2005, “Magnetic Spacecraft Attitude Control: Survey and Some Results”, Control and Engineering Practice, Vol. 13, pp. 357-371.

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