New Aspects in Rotary Magnetostrictive Motor Operation

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New Developments in Rotary Magnetostrictive Motor Operation

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Abstract

Several types of electric motors utilized in servo-mechanism applications, responsible for rotational movement could not deliver the right amount of torque, required fairly large amount of electrical energy and significant space for installation and operation. These shortcomings triggered the idea to develop another type of rotational motor. Following years of intense research, scientists came with magnetostrictive motor. In this paper, the time variation of the magnetostrictive torque was determined and expressed for the full cycle of the periodical current carried by the actuator's coil. The moment of separation between the rotor disk and the flexible friction element was precisely found out. The developed torque is a periodical function of time, with the same cycle as the periodical current carried by the actuator's coil. Furthermore, in the paper was developed an analytical mathematical model which takes into consideration both regimes: the starting process and the running one. In this way, one can track the displacement of the operation point. The developed model includes, in a rigorous manner, the main elements concerning the operation of the magnetostrictive motor. All of the experiments have been performed using a magnetostrictive motor designed and built in-situ by the Department *of Micro and Nano electro technologies,* within the National Institute for Research and Development for Electrical Engineering, Bucharest, Romania. The experimental data confirm and complete the main theoretical developments from the paper.

Keywords: actuator, inductor, magnetostrictive torque, optimal function, rotary magnetostrictive motor

1 Introduction

Several types of electric motors utilized in servo-mechanism applications, responsible for rotational movement could not deliver the right amount of torque, required fairly large amount of electrical energy and significant space for installation and operation. These shortcomings triggered the idea to develop another type of rotational motor. Following years of intense research, scientists came with magnetostrictive motor. This motor is based upon the intrinsic magnetostrictive effect, which is defined as the elongation or contraction of a bar made of magnetostrictive material, following its spontaneous magnetization or as a direct consequence of the increase in the magnetic field acting upon the bar. Several types of magnetostrictive motors, like linear, rotational or stepper, found their own particular places as components of servo-systems. Many literature sources present special electric drive solutions based on magnetostrictive motors, yet unified by a common characteristic: the rotational movement was generated utilizing several linear actuators [1-21].

Recent achievements [14] confirm the development of a magnetostrictive motor type which is capable to perform axial and radial movements. This motor offers a clear solution demanded by the position control in a plain area, using two directions (i.e. two degree of freedom or 2-DOF), with direct application in high precision machining.

The ideal material used in magnetostrictive motors fabrication is known as Terfenol-D. This material has remarkable features, which brands it as the “optimum”: is capable to deliver a magnetic stress of 1000-2000 ppm for a magnetic field of 50 – 200 kA/m in volumetric materials, operates properly for the largest temperature range and displays an acceptable compromise between high tension and high Curie temperature [8-14]. All the properties mentioned above, transformed the magnetostrictive actuator in an important player for fields like the Micro/Nano positioning systems and hydraulic press control. A special category of actuators is represented by the giant magnetostrictive actuators (GMA) [11-14]. In addition to the high Curie temperatures and the large developed stress, the GMA have a large displacement in comparison with the piezoelectric materials. GMM can provide noncontact driving without electrodes, whereas the fabrication process is relatively simple for a multitude shapes [14]. The good performance following a relatively inexpensive fabrication made the GMA suitable for many applications: electro hydraulic servo valves [3], high pressure common rail injectors [12, 13], rotary-linear motion, ultraprecise fabrication operations [14], active vibration control [17], etc.

In some applications the power consumption may become a critical factor, due to drastic local limitations. Such a problem was successfully addressed in [16], resulting a complete three phase actuator kit including the power electronic converter and the DSP based control unit. The magnetostrictive motor shaft position is monitored by a laser based position sensor, and the displacement is controlled by a closed loop system. The system had demonstrated remarkable capability: generated force of 410N, a speed up to 60mm/min and a displacement of 45mm. The power consumption recorded during the tests was only 95W, whereas the actuator has the capability of self-braking, being able to preserve its position if the power is cut-off.

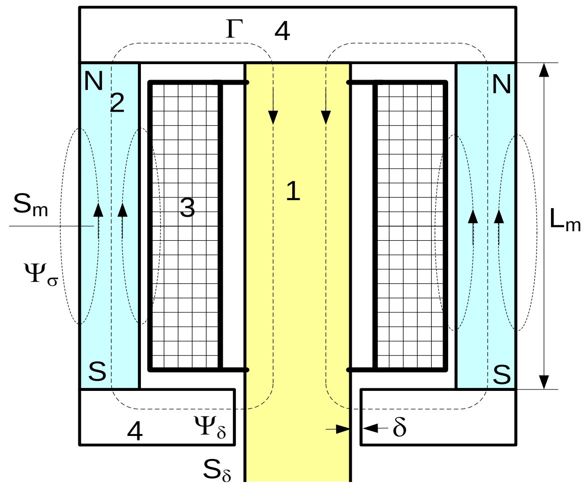
This study has multiple objectives concerning the magnetostrictive motor: developed torque analysis, mechanical characteristic and the comparison between the theoretical and experimental results.

The object of the overall analysis was a rotational magnetostrictive motor, designed and built by the Department of Micro and Nano electro technologies, within the INCDIE ICPE-CA of Bucharest, Romania.

2 Materials and Methods

This section contains a presentation of the actuator components and the transmission mechanism, according to literature [7, 8], [22], followed by the explanation of functional elements and the actuator mode of operation.

In Figure 1, one can visualize the sketch of the actuator utilized in the construction of the magnetostrictive motor under test.



Legend: 1. magnetostrictive rod (core); 2. Permanent magnets cylindrically shaped; 3. Inductor; 4. Lids (Shields); Γ-lines = magnetic field produced by the permanent magnets, ψ_σ lines = leakage magnetic flux

Figure 1. Magnetic circuit of the actuator

The "Terfenol-D" made bar1 is part of the magnetic circuit, subjected to a resultant magnetic field. Two separate sources generate magnetic field. One source is represented by permanent magnets (2), the other by the inductor (3), whose winding carries the current i_b. The magnetic circuit closes in through lids (4). The permanent magnets (2) are shaped as a cylinder and deliver a magnetic field with a trace.

It is well known that the point of operation for a permanent magnet is placed on the "recoil" segment from the magnetizing characteristic [23]. Both, the magnetizing (i.e. along curve Γ), respectively the leakage flux Ψ_σ are indicated in the sketch.

Responsible for "translation to rotation" transmission of the movement is the device presented in Figure 2, where the magnetostrictive core is mechanically coupled to a rotor disk through a flexible friction element.

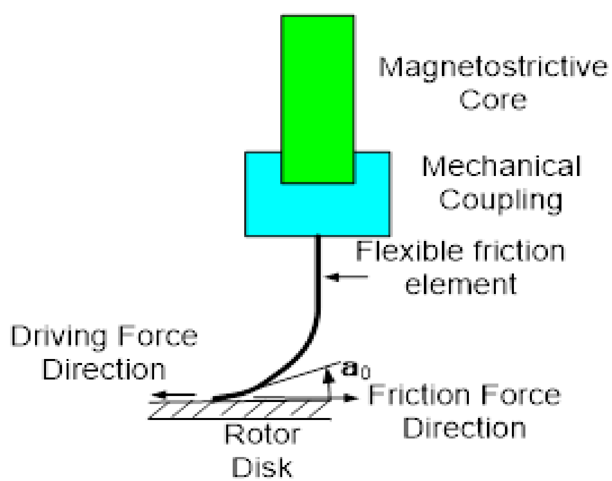


Figure 2. Rotor disk and the transmission mechanism

The micro contact present between the friction element and the rotor disk covers an area bordered by a micro ellipse, fact demonstrated whereas applying the elasticity equations [10]. The relationship between the elongation ΔL of the magnetostrictive bar and the intensity of the magnetic field H is given by (1), whereas the relationship between the inductor current i_b and H is given by (2a, b):

$$\Delta L = \lambda H \tag{1}$$

$$i_b = I_M sin\omega t \tag{2}$$

According to equation (1), the elongation ΔL is a function of magnetic field intensity H, represented by the curve from Figure 3.

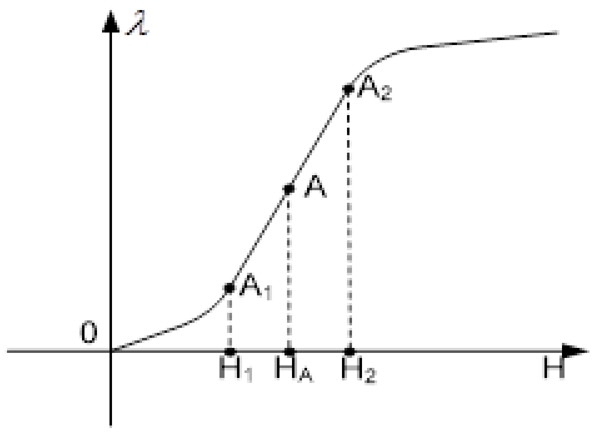


Figure 3. Variation of elongation as a function of magnetic field intensity

The curve contains a linear fragment A_1A_2 characterized by constant elongation λ (i.e. the curve has a constant slope, or the derivative of the function $\lambda=f(H)$ is constant). The increase in the magnetic field intensity moves the elongation value into the saturation zone, where the elongation λ remaining virtually constant. The nonlinear part $0A_1$ of the $\lambda=f(H)$ curve is determined by the magnetic characteristic of the magnetostrictive bar.

The magnetic field produced by the inductor winding is alternating and sinusoidal (i.e. the inductor winding carries alternating sinusoidal current of the intensity i_b, which consequently generates this type of magnetic field) and varies between — H_{bm} and H_{bm}, according to relationship (3):

$$H = H_{bm}\sin(\omega t - \pi) \tag{3}$$

The intervals when the mobile disk is active are described by (4):

$$\omega t \in \left[\frac{\pi}{2} + 2k\pi, \frac{3\pi}{2} + 2k\pi\right], k \in N \tag{4}$$

The increase in elongation ΔL is recorded along the full linear zone of the curve $\lambda=f(H)$. In this way, ΔL is maximized, and, consequently the magnetostrictive motor performs better. The intensity of the magnetic field H_{mp} produced by the permanent magnets must correspond to the point A from the curve represented in figure 3. The electromagnetic torque M which drives the rotor disk can be expressed as:

$$M = Fr_c cos\alpha_0 = \frac{\Delta L}{\lambda_h} r_c cos\alpha_0 \tag{5}$$

In equation (5) r_c is the distance between the point of contact and the shaft of the rotor disk. Then α_0 represents the angle between the vector representing the force F and the plane of the rotor disk. The force F is a direct consequence of the Hooke's Law.

For the increase of the magnetic field H, the elongation ΔL of the magnetostrictive bar increases as well. Consequently, the driving force F increases as well, until the magnetic field intensity reaches its maximum value H_{bm}. Analysing the relationship (5), one can figure out the increase recorded for the active torque M, which is responsible for the rotor disk movement. Whereas the magnetic field H decreases, the driving force F decreases as well, determining a decrease in the active torque M. At this point of the operation, whereas the magnetic field intensity H is close to H_{bm}, the friction element (see figure 2), experiences a weaker adhesion to the disk surface, behaving like a spring.

Therefore the torque has a periodical variation with respect to the angle of rotation, expressed in radians, described by (6), [23].

During a cycle T of the current i_b, the torque can be expressed in per unit by (6):

$$\frac{M}{M_m} = \begin{cases} \frac{1}{2}(1 - cos\omega t), \omega t \in \left[0, \frac{7\pi}{6}\right] \\ 0, \omega t \in \left[\frac{7\pi}{6}, 2\pi\right] \end{cases} \tag{6}$$

The friction element (see figure 2), becomes less adhesive to the disk, whereas the elongation decreases by 0.10 to 0.15 from its total value recorded at the angle $\omega t = 7\pi/6$. The periodical function representing the time dependent torque is given by (7), following the Fourier series decomposition:

$$M(t) = M_0 + \sum_{k=1}^{\infty} M_{km} cos(k\omega t + \alpha_k) \tag{7}$$

3 Results and Discussions

When considering $f=100Hz$ (i.e. $T=1/f=0.001s$), the coefficients from expression (7) are determined utilizing the MAPLE software. Conventionally, the maximum value of the function $M(t)$ was chose to be equal to 1. The real torque expression depends on the circumstances of the application and can be obtained from (7) through simple multiplications [1], [23].

The average value M_0 of the function $M(t)$, the magnitudes of the harmonics, respectively the phase shifts between harmonics are displayed by the figures 4 and 5. Figure 4 reveals a predominance of the average value M_0 over the magnitudes of harmonics, whereas the harmonics having an order superior to 3 can be neglected. In fact, during the energy conversion process associated to the running regime, the average torque value is the most important. The phase shifts between harmonics (see figure 5) don't affect the energy conversion process significantly. The presence of harmonics may become important during the dynamic regimes of the magnetostrictive motor.

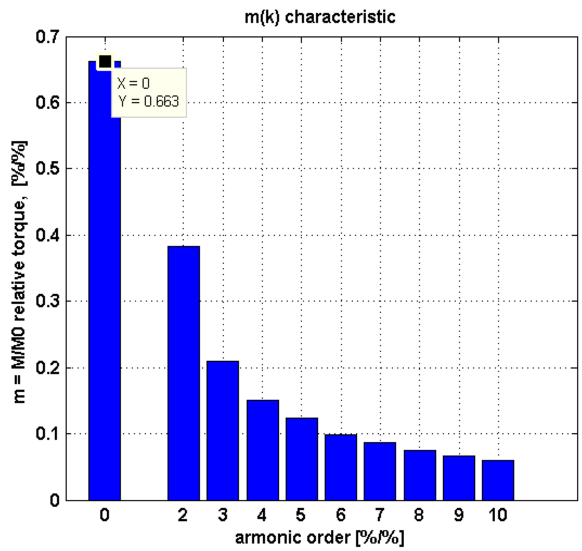


Figure 4. The average value and the magnitudes of harmonics for the torque M

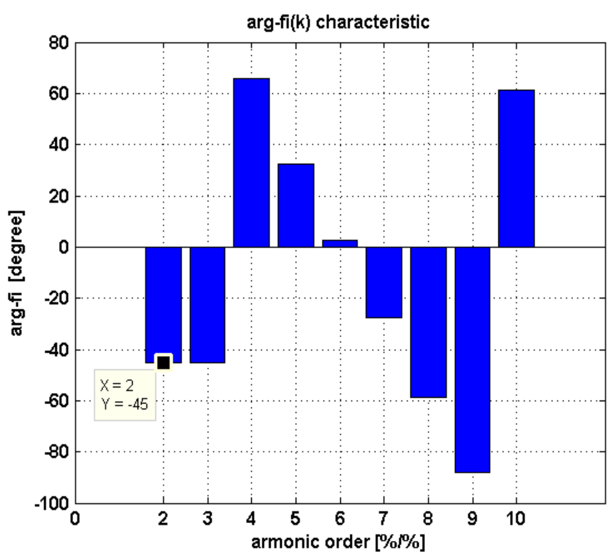


Figure 5. Phase shift between the harmonics from the torque curve

The restriction of the interval of active torque to (0; $7\pi/6$) results in the diminishing of the average torque, and subsequently into the diminishing of the motor efficiency. The exact determination of the interval of active torque requires adequate experiments.

The rotational speed *n* is a consequence of the motion equation for every single motor. In the case of magnetostrictive motor, the motion equation can be pulled out in conditions of running at constant rotor angular speed, as following (8a-c):

$$J\frac{d\Omega}{dt} = J\frac{\pi}{30}\frac{dn}{dt} = M(t) \tag{8a}$$

$$M(t) = M_0 + \sum_{k=1}^{\infty} M_{km} cos(k\omega t + \alpha_k) \tag{8b}$$

$$n = \frac{30}{J\pi} M_0 t + \frac{30}{J\pi} \sum_{k=1}^{\infty} \frac{M_{km}}{k\omega} sin(k\omega t + \alpha_k) \tag{8c}$$

Equation (8) expresses the mechanical characteristic of the magnetostrictive motor n=f(M) at a given frequency of the power supply which energizes the inductor. J is the moment of inertia of the system in rotational motion. The torque can be expressed as a function of frequency in the form of M(t) = f M_1, with M1 the torque developed at 1 Hz. According to equation (6), one can extract very useful conclusions. First of all, the motor cannot operate unloaded. The first term from the mechanical characteristic, discloses a linear rotational speed dependency with time. The explanation for this fact relies on the independence between the average torque M_0 and the rotational speed *n*.

Consequently, the mechanical characteristic cannot be defined for every possible load torque Ms. Furthermore, percent wise, a harmonic of the rotational speed has smaller magnitude in comparison to the torque harmonic having the same order. The harmonic amplitudes of the rotational speed are inversely proportional to their order and with the pulsation of the current carried by the inductor coil. For the value of frequency below 1 Hz, the magnitudes of rotational speed harmonics can reach significant values. During the main process of energy conversion, at starting and running as well, the higher order harmonics of are neglected. One segment of the sinusoidal torque-time curve, recorded from the moment of the energizing the inductor until the torque reaches the average value M0 is further on studied (see Figure 6). Initially (t=0) it was assumed a stationary rotor disk (n=0). During the starting process, the operating point migrates along the first segment of the magnetostrictive torque–time curve (see figure 6), then follows the average torque M_0 for few moments, finally being settled at a specific value demanded by the load *Ms*. The torque represented in Figure 6, determines the characteristics of the motion and can be analytically described by the relationship (11a). The time constant T_c was selected by imposing the value the torque-time curve slope between 0 and M_0. The slope value must be obtained after solving (10), (11). The final value of the angular speed is a consequence of the rotor motion equation as described by the procedure (9), (10):

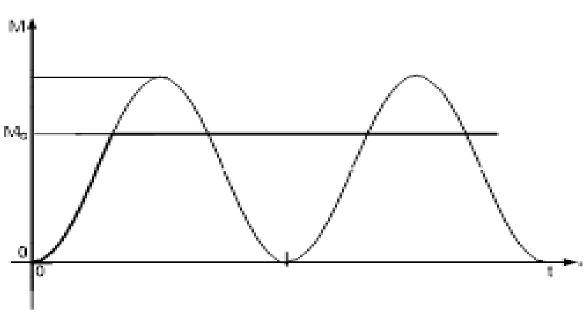


Figure 6. Time variation of the torque

$$J\frac{d\Omega}{dt} = J\frac{\pi}{30}\frac{dn}{dt} = M - M_r \tag{9a}$$

$$M_r = M_C + M_D + M_S;\ M_D = D\Omega;\ M_C = const. \tag{9b}$$

$$\xrightarrow{(8a,b)} J\frac{d\Omega}{dt} = M - M_r = M - (M_C + M_D + M_S) \tag{9c}$$

We've made the assumption of having the torque developed by the actuator in the form (10a):

$$M = M_0\left[1 - e^{e^{\left(-\frac{t}{T_C}\right)}}\right] \tag{10a}$$

Then, the dynamic equation for rotational movement is (11b). The time variation of the rotational speed is found following the steps (10b-h):

$$\frac{d\Omega}{dt} + \frac{D}{J}\Omega = \frac{M_0}{J}\cdot\left(1 - e^{\left(-\frac{t}{T_C}\right)}\right) - \frac{M_C + M_S}{J} \tag{10b}$$

$$\xrightarrow{(9a,b)} \frac{d\Omega}{dt} + \frac{D}{J}\Omega = k_{m1} - k_{m2}e^{\left(-\frac{t}{T_C}\right)} \tag{10c}$$

$$\frac{d\Omega}{dt} + k\Omega = k_{m1} - k_{m2}e^{\left(-\frac{t}{T_C}\right)};\ k = \frac{D}{J} \tag{10d}$$

$$k_{m1} = \frac{M_0 - (M_C - M_S)}{J};\ k_{m2} = \frac{M_0}{J} \tag{10e}$$

$$F(t) = 1 - e^{-kt} \tag{10f}$$

$$G(t) = 1 - e^{\left(-\frac{t}{T_C}\right)} \tag{10g}$$

$$\Omega = \frac{k_{m1}}{k}F(t) + \frac{k_{m2}}{k - 1/T_C}e^{(-kt)}G(t) \tag{10h}$$

In the expressions from above, there are following significances:

M_C - Torque associated with Coulomb type frictions (M_C = constant): it speed invariant;
M_D - Torque due to viscosity (i.e. frictions in the bearings);
M_s - Load torque demanded by the driven installation or machine;
M - Active torque, responsible for maintaining the movement;
T -Time duration of the current cycle;
M_r - Total (resultant) torque which opposes to the rotational movement.

For the particular case described by the $k=0$ and $M_r=0$ (i.e. unloaded operation), the motion equation is described by:

$$J\frac{d\Omega}{dt} = M = M_0\left[1 - e^{\left(-\frac{t}{T_C}\right)}\right] \tag{11a}$$

$$\Omega = \frac{\pi n}{30} = \frac{M_0}{J}t + \frac{M_0}{J}T\left[e^{\left(-\frac{t}{T_C}\right)} - 1\right] \tag{11b}$$

However, whereas the relationships (11b) is analysed, the unloaded operation becomes impossible without the presence of the factor *k* (i.e. *k* must not be equal to zero). For a factor *k* different from zero, the angular speed Ω reaches a constant value at the end of the transient represented by the starting process. This now determined value of the angular speed is directly correlated to the power loss due to the friction in the bearings. The operating angular speed (12) is established after a longer time interval:

$$t \to \infty \Longrightarrow e^{\left(-kt-\frac{t}{T_C}\right)} \equiv 0;\ e^{(-kt)} \equiv 0 \tag{12a}$$

$$\Omega = \frac{\pi n}{30} = \frac{k_{m1}}{k} = \frac{M_0 - (M_C + M_S)}{J} \tag{12b}$$

$$k \to 0 \Rightarrow \Omega \to \infty \tag{12c}$$

If the total inertia has a very small value, then rotational speed can theoretically reach extremely large values. The dependencies $\Omega = f(M_s)$ and/or $n = f(M_s)$ denote the mechanical characteristic of the revolving magnetostrictive motor. This characteristic has the shape of a line with negative slope, which decreases with the increase in the load torque M_s. If the factor $k = 0$, the magnetostrictive motor goes runaway. The magnetostrictive motor subjected to experiments and tests was designed and built in-situ by the Department of Micro and Nano electro technologies, within the National Institute for Research and Development for Electrical Engineering, Bucharest, Romania (see Figure 7).

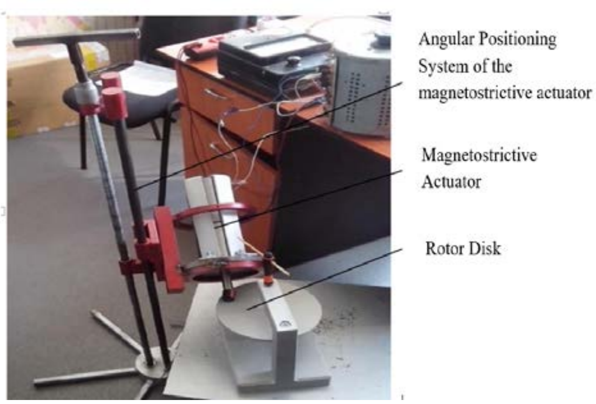


Figure 7. Rotary magnetostrictive motor

The measured values included the power supply voltage *U* which was applied across de inductor's winding, the frequency f a of the power supply voltage, the rotational speed n of the rotor disk, respectively the load torque. All results have been recorded in Table 1.

U[V]	f[Hz]	n[rpm]	M_S[Nm]
100	100	6	$36x10^{-3}$
100	100	5	$40 x10^{-3}$
100	100	3	$43 x10^{-3}$
100	150	8	$52 x10^{-3}$
100	150	7	$58 x10^{-3}$
100	150	5	$61 x10^{-3}$

Table 1. Recorded performances of the magnetostrictive motor

The measurements data have been acquired for two values of the power supply (excitation) frequency: 100 Hz and 150 Hz. Whereas comparing the mechanical characteristics $n = f(M_s)$ traced for the two frequency values, one can understand the correlation with relationship (12). The magnetostrictive torque is obviously proportional to the frequency. If M_1 represents the torque at frequency M_1, then the torque recorded for the frequency f is equal to $M = f\, M_1$.

4 Conclusions

This paper was focused on obtaining a proper expression of magnetostrictive torque as function of time, during a cycle of the periodic current carried by the actuator coil. The moment of separation between the rotor disk and the flexible friction element was accurately sorted out, and the time function of the magnetostrictive torque was found out periodical with a period equal to the period of the current carried by the actuator's coil. This periodic function was converted into a Fourier series. The term denoting the average torque M_0 is the predominant term, in the newly formed Fourier series representing for now the magnetostrictive torque. All harmonics with order greater than three can be neglected. Only the average developed torque value is essential, whereas the phase shifts between harmonics have no remarkable impact on the energy conversion process. The magnetostrictive motor cannot operate unloaded, and this conclusion may be evident from the rotational motion equation, even at the first sight. The lack of capability to operate unloaded is motivated by the fact that the average developed torque M_0 is independent of rotational speed. Obviously, the mechanical characteristic cannot be defined for every load torque M_s. Percentwise, a harmonic of rotational speed has much lower amplitude then the torque harmonic of same order, affirmation valid for all harmonics under consideration. A harmonic of the rotational speed has an amplitude which is inversely proportional with respect to its order and the value of the pulsation of the current carried by the actuator's coil. Eventually, if the excitation frequency drops below 1 Hz, then the rotational speed harmonic amplitude can reach quite high values. Furthermore, in the paper was developed an analytical mathematical model which takes into consideration both regimes: the starting process and the running one. In this way, one can track the displacement of the operation point on the torque – time curve. The developed model includes, in a rigorous manner, the main elements concerning the operation of the magnetostrictive motor. All of the experiments have been performed using a magnetostrictive motor designed and built in-situ by the

Department of Micro and Nano Electro technologies, within the National Institute for Research and Development for Electrical Engineering, Bucharest, Romania. The experimental data confirm and complete the main theoretical developments from the paper.

References

[1] J. S. Park, O. K. Oh, Y. W. Park, and N. M. Wereley, "A novel concept and proof of magnetostrictive motor ," IEEE Transactions on Magnetics, vol. 49, no. 7, pp. 3379 – 3382, 2013.

[2] Zhi Li, Xiuyu Zhang, Guo-Ying Gu, Xinkai Chen, and Chun-Yi Su, "A Comprehensive Dynamic Model for Magnetostrictive Actuators Considering Different Input Frequencies With Mechanical Loads," IEEE Transactions on Industrial Information, vol. 12, no . 3, JUNE, pp. 980 – 990, 2016

[3] S. Karunanidhi, M. Singaperumal, "Design, analysis and simulation of magnetostrictive actuator and its application to high dynamic servo valve," Sensors and Actuators A: Physical, vol. 157, pp. 185-197, 2010.

[4] M. Niu, B. Yang, Y. Yang, G. Meng, "Dymanic modelling of magnetostrictive actuator with fully coupled magneto-mechanical effects and various eddy current losses," Sensors and Actuators A: Physical, vol. 258, pp. 163-173, 2017

[5] J. Zhou, Y. Pan, M. Huang, "A novel magnetostrictive drive rotary motor," Solid State Phenomena Vols. 121-123, pp. 1203-1206, 2007. Online available since 2007/Mar/15 at www.scientific.net Trans Tech Publications, Switzerland, doi: 10.4028 /www.scientific.net /SSP.121-123.1203.

[6] Y-W. Park, M. Noh, "Rotary magnetostrictive motor using helical magnetic field," International Journal on Precision Engineering and Manufacturing, vol.17, no.5, pp. 659-663, 2016.

[7] Z. Cao and J. Cai, "Design of a giant magnetostrictive motor driven by elliptical motion," Sensors and Actuators A: Physical, vol. 118, pp. 332-337, 2004.

[8] J. M. Vranish, D. P. Naik, J. B. Restorff, and J. P. Teter, "Magnetostrictive direct drive rotary motor development," IEEE Transactions on Magnetics., vol. 27, pp. 5355-5357, 1991.

[9] F. Claeyssen, N. Lhermet, R. Letty, and P. Bouchilloux, "Design and construction of a resonant magnetostrictive motor," IEEE Transactions on Magnetics, vol. 32, pp. 4749-4751, 1996.

[10] A.M, Morega, M. Popa, Mihaela Morega, L. Paslaru-Danescu, "Shape and structure optimization of a magnetostrictive cored actuator," Int. J. of Heat and Technology, vol.34, Special Issue 1, pp.119-124, 2016, http://dx.doi.org/10.18280/ijht.34S115

[11] L. Paslaru-Danescu, A.M. Morega, Mihaela Morega, "A novel magnetostrictive injection actuator based on new giant magnetostrictive material," The 7th International Symposium on Advanced Topics in Electrical Engineering, ATEE 2011,Bucharest, Romania, May 11-14, 2011, IEEE Xplore, ISBN:978-1-4577-0507-6.

[12] G. Xie, P. Zhang, Z.He, D. Li, Z. Yang, Z. Zhao, "Displacement model and driving voltage optimization for a giant magnetostrictive actuator used on a high-pressure common-rail injector," Materials and Design, vol.95, pp.501-509,2016.

[13] G. Xue, P. Zhang, Z. Xue, D. Lin, Y, Huang, W. Xie, "Design and experimental study of a novel giant magnetostrictive actuator," Journal of Magnetism and magnetic materials, vol. 420, pp. 185-191, 2016.

[14] H. Yoshioka, H. Shino, H. Sawano, "A newly developed rotary-linear motion platform with a giant magnetostrictive actuator" CIRP Annals-Manufacturing Technology, vol.62, pp371-374, 2013.

[15] L. Paslaru-Danescu, A.M. Morega, Mihaela Morega, Florentina Numea, P. Marius, Corina-Alice Barbutanu, "A new type of magnetostrictive *motor,"* Electrical Engineering, vol. 99, no.2, pp.610-613, Springer Link, 2017.

[16] W.K Kim, A. Sadighi, "A novel-low power linear magnetostrictive actuator with local three-phase excitation," IEEE/ASME Transactions on Mechatronics, vol.15, no.2, p. 299-307, 2010.

[17] F. Braghin, S. Cinquemani, F. Resta, “A model of magnetostrictive actuators for active vibration control,” Sensors and Actuators A: Physical, vol. 165, pp.342-350, 2011.
[18] W. Zhu, L.X. Bian, L. Chung, X.T. Rui, “Nonlinear compensation and displacement control of the bias-rate-dependent hysteresis of a magnetostrictive actuator,” Precision Engineering, vol. 50, pp. 107-113, 2017.
[19] R. Joshi, R. Kadoli, “Magneto-mechanical coupled magnetostriction model for Terfenol-D under step input,” International Conference on Advances in Manufacturing and Materials Engineering, Procedia Material Science 5, pp.154-163, 2014.
[20] C.C. Hong, “Application of magnetostrictive actuator,” Materials and Design, vol. 46, pp. 617-621, 2013.
[21] A.M. Morega, P. Marius, Mihaela Morega, “Optimizarea unui actuator magnetostrictiv (The optimization of a magnetostrictive actuator),” Simpozionul de Masini Electrice, SME-14, University “POLITEHNICA” of Bucharest, Romania, October 3rd, 2014 (in Romanian).
[22] M. Ignat, N. Galan, A. Dalea, “Short Introduction on the magnetostrictive motor,” Bulletin of Micro and Nanoelectrotechnologies, no.1-2, pp. 29- 34, 2015,
[23] M. Ignat, G. Zarnescu, I. Puflea, Al. Catanescu, L.Paslaru, V. Stoica, ”Actuatori electromagnetici (Electromagnetic Actuators),”, Ed. Electra, 2008, pp. 22-50 (in Romanian).

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