2nd INTERNATIONAL CONFERENCE ON
RESEARCH IN SCIENCE AND TECHNOLOGY
Istanbul-Turkey 14 March 2016
RSTCONF
دومین کنفرانس بین المللی پژوهش در علوم و تکنولوژی
ترکیه - استانبول ۲۴ اسفند ۱۳۹۴

A process of measurement, and calibration of magnetic torquer by using Kosar 100 system

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Abstract
In this paper, we have explained an operational method, and test procedure, which can be used to recognize, and evaluate accuracy of the magnetic dipole, and the generated torque by magnetorquers. This process is based upon usage of the satellite orbital magnetic surroundings simulator system (Kosar 100).As in this manner all the external factors affecting the test results are eliminated by the mentioned system therefore the results achieved are more accurate and reliable. On the other hand, this testing method can be used to develop (edit) characteristics of newfound materials in magnetic space scope as magnetorquer cores.

Keywords: Magnetic dipole moment, Magnetic field simulator, Space system testing equipment, Magnetorquer

1. Introduction

When satellites are located in the orbit, to deal with unwanted turbulent torques, and to satisfy the mission requirements, it is needed to use control elements. These elements, by generating torques, assist satellite in controlling, and switching the situation. Magnetorquers or magnetic operators are one of these elements that used to generate magnetic dipole moments for compensate for residual spacecraft biases and to counteract attitude drift due to environmental disturbance torques. Especially, they are used for reducing turbulence and controlling the status of the satellites when it is going to be located into the orbit. On the other side, the low mass, small size, low cost, and low power consumption are the other properties of magnetorquers, and due to these reasons, small satellite in low-earth-orbit (LEO) are using this type of control elements.

Produced magnetic dipole, by magnetorquers, interacts with orbital magnetic field, and generate control torque. Control torque is a determining factor for satellite designers, and due to what has already mentioned and as a result of that, produced dipole magnetic by magnetorquers is important and determinant factor as well(Wertz 1996). It may also be clarified that the amount of produced dipole magnetic, and produced hysteresis are two major criteria to select magnetorquers for special satellite. On this basis, and to study and test the produced magnetorquers with high precision, satellite orbital magnetic surroundings simulator system (Kosar 100) was manufactured in space research laboratory of Khajeh Nasireddin Toosi University of technology.

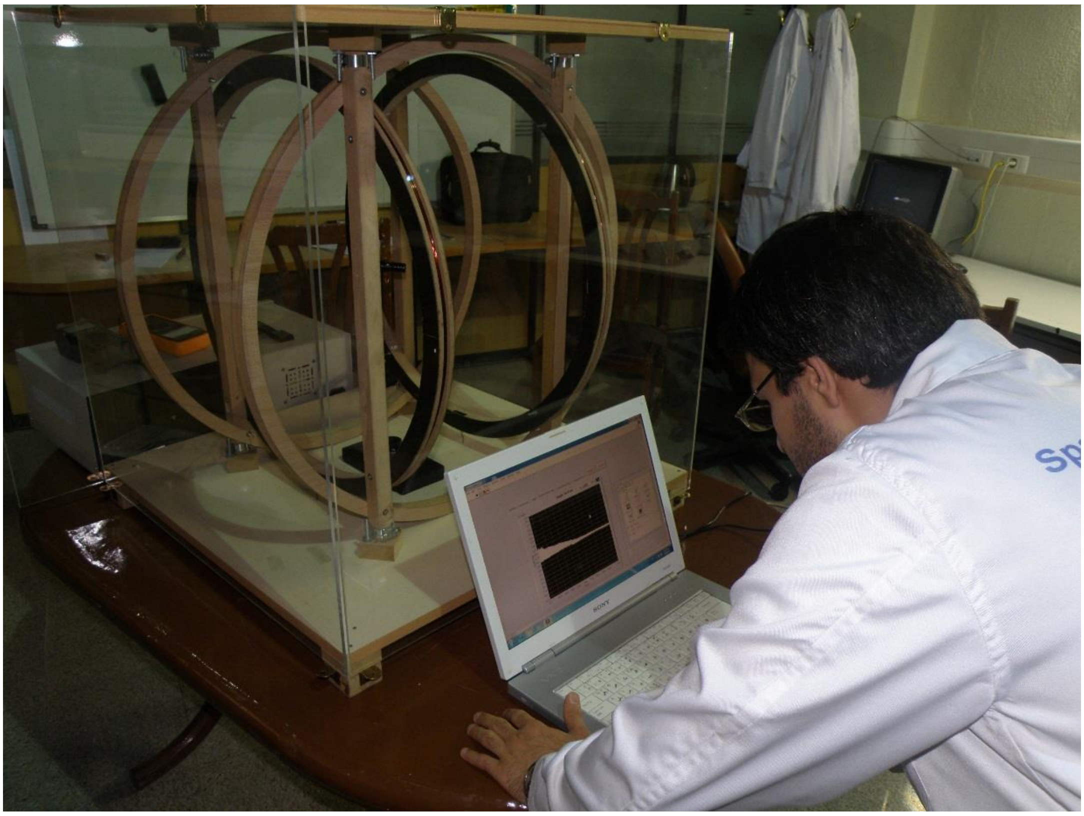

Figure 1 -Kosar 100 testing process in Space research lab.

In this article, we have described a testing algorithm, which based on that, and by using the mentioned system, we will be able to test the produced magnetic cores towards its capability for doing the operation, and amount of the generated dipole magnetic. It will also let us to evaluate and test new materials to suggest as a new core for magnetorquer core (Reitz et al, 2007).

2. The activities that has been done on the field of magnetorquers calibration

Since there isn't a direct way to determine the magnetic torque in small magnetorquers, especially used in mini and micro satellites, therefore we do our best to measure these parameters in our experiments and laboratories. Measurement of magnetic flux on the magnetorquer axis, Is the basis of all the experiments. Designers of this methodology believe that this experiment requires high precision and sensitivity because of high effective factors that affected our system. In 2002, J. Lee, published a paper in Aerospace journal of Canada, which describes the basic mathematical- physical facts of this experiment (Lee et al, 2002). Also, in1993, Stelter produced a Helmholtz coil and introduced new and low cost method for magnet test (Stelter, 1993). Moreover, Guelman published a paper and described testing and design of magnetic controllers in 2005 (Guelman et al, 2005). In 2013, Li J. and his coworkers presented a satellite attitude control system design using low-cost hardware and software for a 1U CubeSat (Li et al, 2013).

3. The satellite orbital magnetic surroundings simulator system (kosar 100)

Kosar 100 system, is composed of two perpendicular Helmholtz coils, which has the purpose of generating a controllable and unified magnetic field. Two uniform magnetic fields can then be generated in a cylindrical area with 12 cm of radius and 16 cm of height with 0.01 Gauss precision.

3.1 The kosar 100 simulator parts

I. Two pair Helmholtz coils which are Perpendicular. Figure2 shows the square between two coils and precision of produced magnetic field that measured by magnetometer. In this figure, X and Y coordinate axes demonstrate to central line of coils and Z axis demonstrates to magnitude of magnetic field that produced in line X axes.

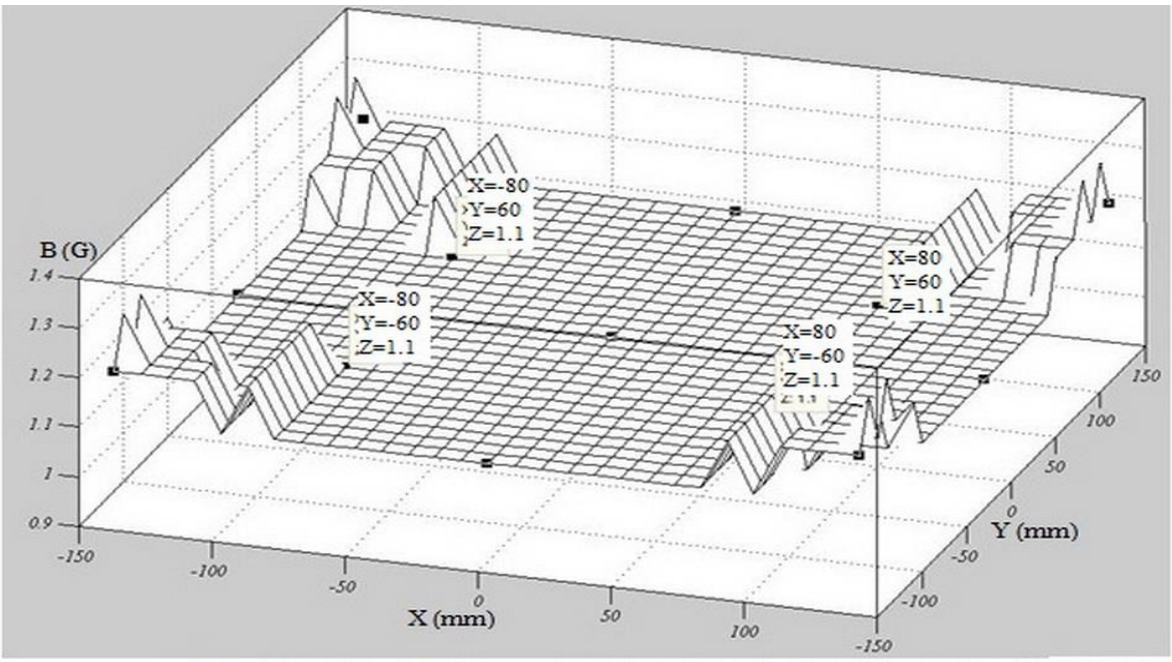

Figure 2-magnetude of magnetic field simulated by kosar100

II. Magnetometer that used to measure the magnitude of surround magnetic field

III. The simulator is equipped with an electrical driver, which is designed to generating a proper magnetic field with regard to the angle and the magnetic field magnitude.

IV. The image processor sensor which is connected to this simulator provides us Images which illustrate the possibility of processing each move of the magnetorquer (with the precision of 0.1 degree).This processor is a 2D camera that uses Matlab toolbar. Figure3 shows two views of kosar100 vision processor.

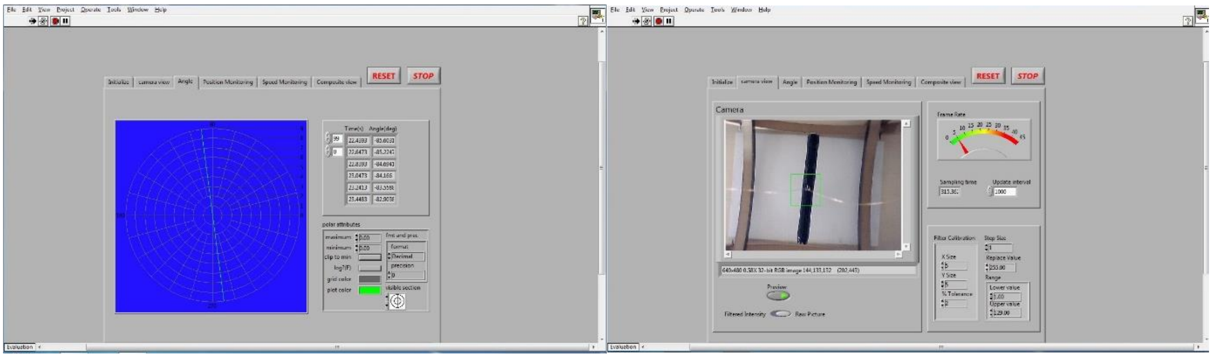

Figure 3-two view of kosar100 vision processor

V. The central processor program that processes all internal and external factors and controls simulators parts. This program based on Matlab programming and jointed with magnetometer and vision processor.

3.2 How kosar 100 works?

Central processor compared Magnitude and direction of desired magnetic field had been entered by user with surrounding magnetic field and determine the magnitude of electrical current which have to drive in Helmholtz coils in order to compensate the effect of Earth's magnetic field inside the Helmholtz cage and produce desired magnetic field. Image processor sensor sensed magnetorquer rotation and transferred data to central processor program. Finally, data is processed by processor program and determined the magnetic dipole vector, as well as, determination of magnetorquer torque vector. In addition to the applications that are mentioned so far, kosar100 is applicable in examination of magnetorquer operation in real conditions and extraction of control modes and controlling the torque, which is generated via a magnetorquer. In figure 4, mentioned process has been depicted.

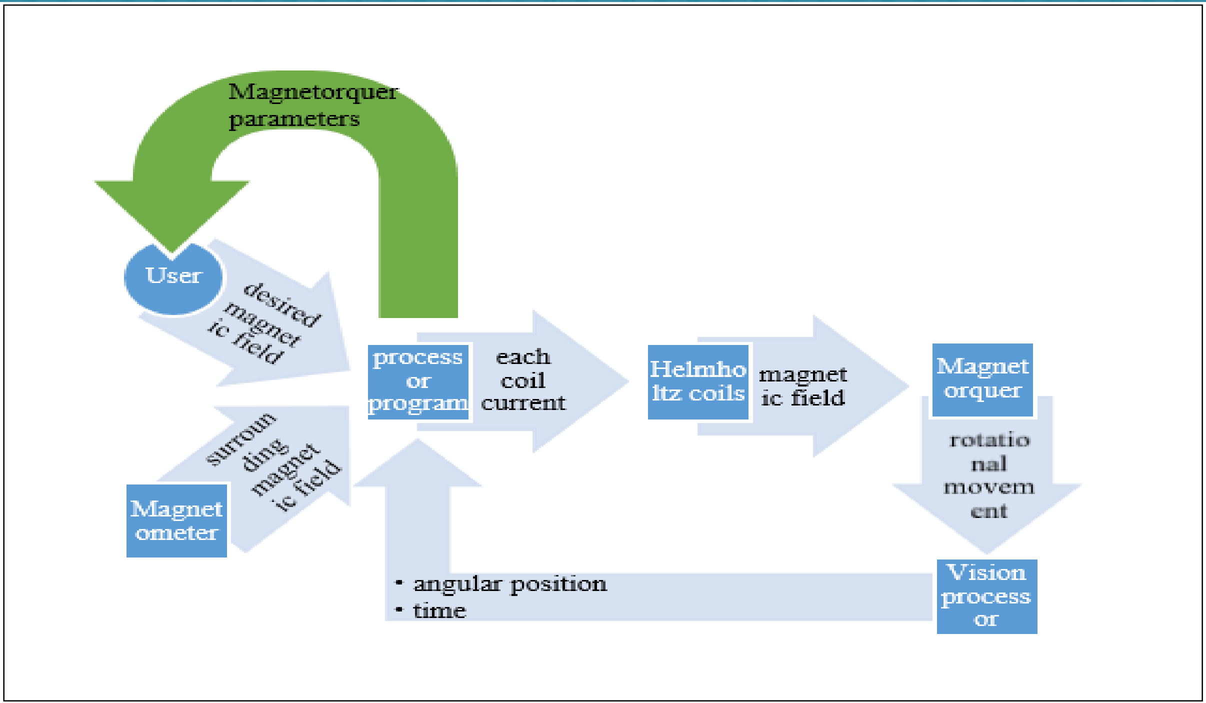

Figure 4-Kosar100 process diagram

3.2 New process preference

Nowadays, J. Lee common procedure is used to determine magnetorquer parameters which based on determination of magnetic flux on the axis of the magnetorquer. There are two possibilities which can decrease precision in determination of magnetic flux on the axis of the magnetorquer, firstly, the earth's magnetic field is not zero and secondly, the human error.

This simulator has the ability to compensate the effect of Earth's magnetic field inside the Helmholtz cage the entire earth's magnetic field. Moreover, the image processor sensors have the ability to reduce the human error in both measurement and locating. We can infer that comparing to the other methods; the mentioned simulator is capable of augmenting the precision.

4. Theoretical basis

The current flow in coils of magnetorquer's orbit, create magnetic field. The magnetic field will pass through the ferromagnetic core and generate a magnetic dipole(M), which will interact with the earth's magnetic field(B) and eventually generate a torque(T) as equation 1(Wertz 1978) (Reitz et al, 2013).

$$\vec{T} = \vec{M} \times \vec{B} \quad \& \quad |T| = MBSin\theta \qquad (1)$$

Via using electromagnetic equations, we are able to equate every magnetic dipole generator with an electric orbit. And in the absence of a ferromagnetic core, we are able to apply equation 2.

$$\vec{M} = ni\vec{A} \qquad (2)$$

4.1. The necessity of applying practical methods, rather than applying theoretical methods in determination of M

Magnetorquer score is a ferromagnetic alloy with low hysteresis, linear magnetic flux with electric current and high permeability coefficient. In such circumstances, in consequence of equation 2, equation 3 will be obtained.

$$\vec{M} = kni\vec{A} \qquad (3)$$

For a magnetorquer, with an air core, the core efficiency factor (k), will be 1. For coils with ferromagnetic alloy core, this index will be among 100-300. Also for magnetorquer with ferromagnetic cores, considering the following features: core's length to equivalent diameter ratio, the cross-section form and core's magnetic permeability, the index will be determined (Li et al, 2013) (Wertz 1978).
As mentioned previously, in achieving a producible torque, determination the dipole magnetic in magnetorquer is obligatory. Since core efficiency factor is depend on several factors, besides such index hasn't been estimated for new alloys, consequently, applying equation 3 for acquiring the magnetic dipole torque for a magnetorquers not feasible. In order to figure out a solution for such problem, we require considering the magnetorquer movement in simulated magnetic field and applying the kosar 100 system to propose a method for measuring the M. In such method, the first step in determination of magnetic dipole, which is recorded by the sensors, the next step will be the announcement of control torque (which is generated via magnetorquer), by kosar 100 to the user, as a function of the angle and maximum value.

4.2. Determination basis for magnetic dipole and torque vectors of magnetorquer via kosar100 system

Briefly the computer program, which is designed for kosar 100, will extract a function for movement of magnetorquer. Such functions ($\theta(t)$), can be extracted from the data that has been recorded via vision processor sensor and consequently apply that function for calculating the torque vector and magnetic dipole. Such fact is the basis of an algorithm that is applied and will describe in this section.

4.2.1. Description of magnetorquer movement under the influence of unified magnetic field

When constant electric current, which is generated in a magnetorquer, is influence by a unified field, a torque will affect the magnetorquer and consequently, it will return the magnetorquer to the center of oscillation. Center of oscillation (according to equation 1) is a point in which the angle between two vectors (M and B), is zero. The tested magnetorquer, suspend via a wire (with low torsional coefficient, k) in kosar100 and will generate torque. As a result of the generated torque, equilibrium canter moves to another point. At this point (coil with air core or any other material), total torque in magnetorquer will be zero (figure 5).

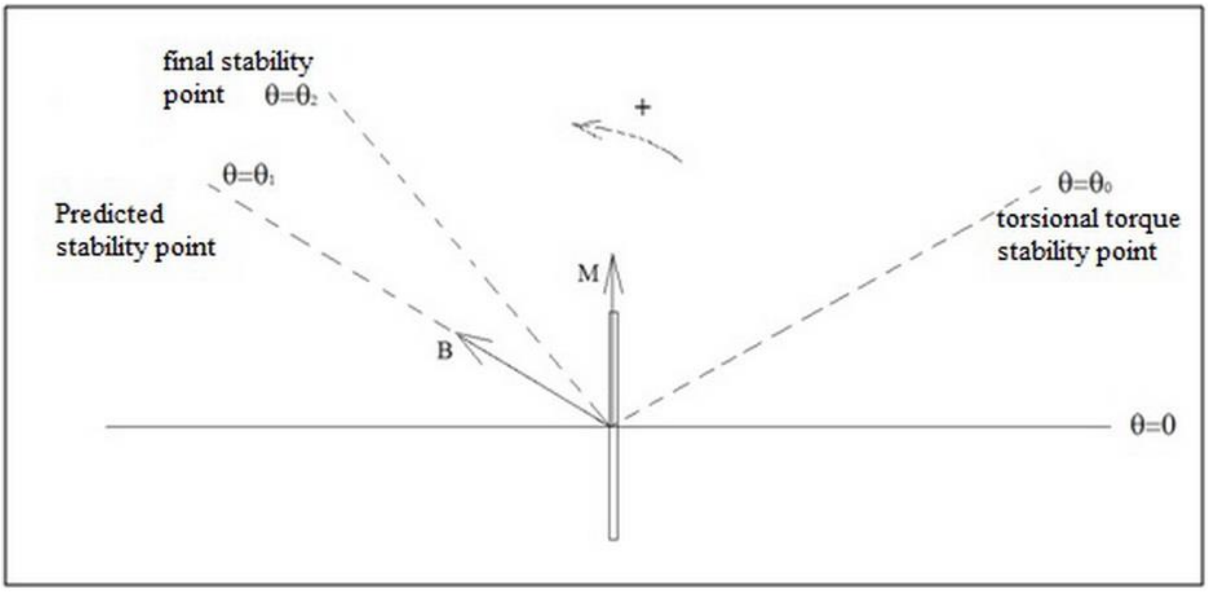

Figure 5-Important angles position in described algorithm

Equation 4, shows the existence of torque in magnetorquer. Moment of inertia, which stores in magnetorquer, will cause the magnetorquer to continue it's way and pass the oscillation center. Consequently, both torque vector direction (T) and angle (θ) will reversed. As a result of this event, returning torque will occur, which will return the magnetorquer to back to the oscillation center. In the mentioned cycle, the peak-to-peak amplitude tends to decrease, until the magnetorquer reaches an equilibrium state and stop moving. The magnetorquer acts like a mass in a damper- spring system.

$$I\,\ddot{\theta} = -K(\theta - \theta_0) + MB\,Sin(\theta_1 - \theta) \quad (4)$$

In figure 6 we can observe the movement of damper-spring system. Also in figure 7, we can observe the diagram of sensed magnetorquer movement.

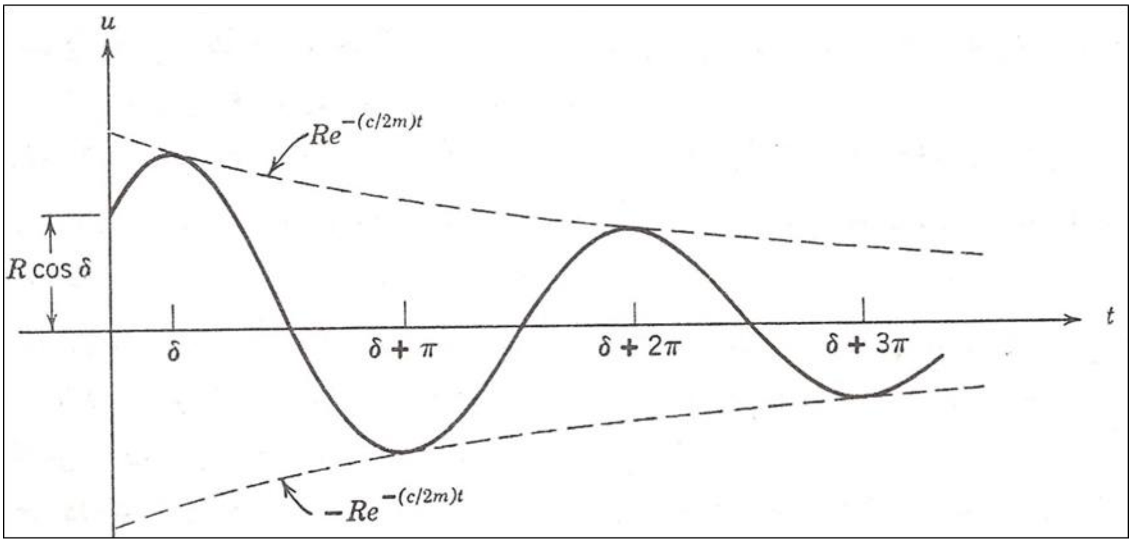

Figure 6-movement of damper-spring system

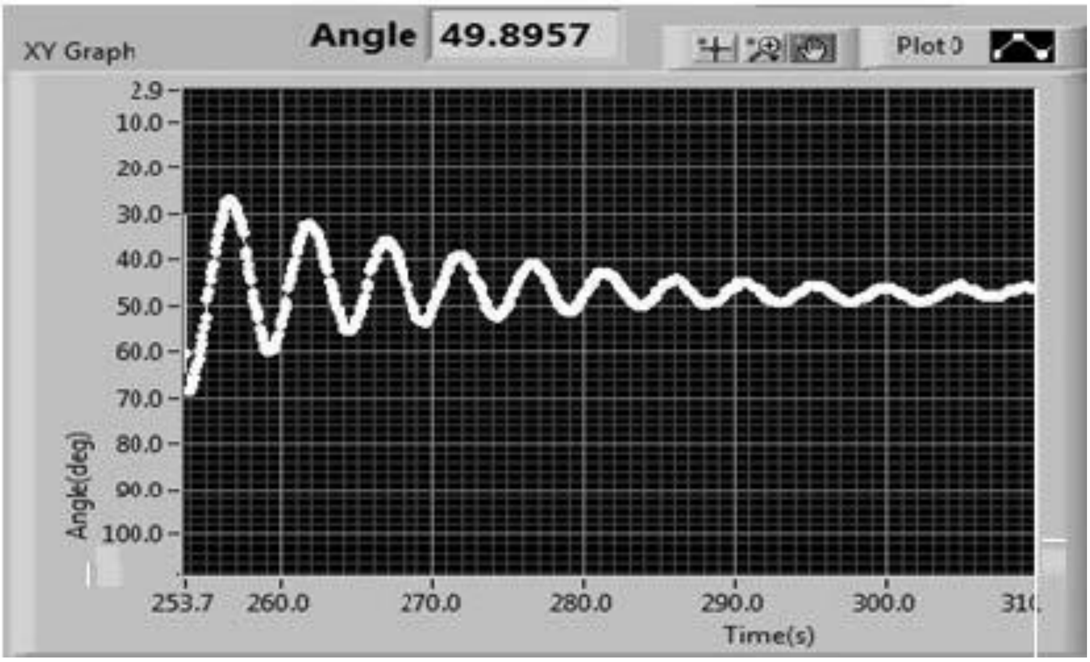

Figure 7-diagram of sensed magnetorquer movement

Considering the conformation of two diagrams, we can declare that mass movement equilibrium and magnetorquer equilibrium are equivalent (equation 5).

$$\theta(t) = e^{-At}(R\,cos(\omega t + \delta)) + D \qquad (5)$$

4.2.2. Equations for magnetorquer movement in unified field

Via an existing torque in magnetorquer movement, we designed a differential equation (equation 4). In such equation, not only M and K terms are unknown, but also it can't be resolved via analytical and numerical methods, Laplace equation or boundary conditions. Accordingly, considering the physical condition, we guessed the answer of the equation (equation 5). In this equation, we observe five unknowns, which two of them can be resolved via boundary condition. Solving the mentioned equation also was not feasible. Eventually, we apply an approximated approach, which is in agreement with the purpose of magnetorquer in satellites.

In reality, by functioning the magnetic operators in satellites, magnetorquer will pass through the distance between two angels of θ_0 to θ_2, this transition occurs in the first peak (figure 7). It is feasible to approximate movement of magnetorquer via a quadratic equation (e. g. equation 6).

$$\theta(t) = At^2 + Bt + C \qquad (6)$$

Via generated data from the sensors, we are able to extract the unknown index and consequently extract movement function in the distance between two angels (θ_0-θ_2). The difference between the real data and quadric approximation function is also shown in figure 8. In this figure Z(t) is a function in equation5 format and V(t) is a function in equation6 format and H(t) is the difference between Z(t) and V(t) function. Maximum amount of H(t) function between two angels θ_0 and θ_2 is about 0.005. This showed that we can use equation6 for magnetorquer movement between θ_0 and θ_2 angles.

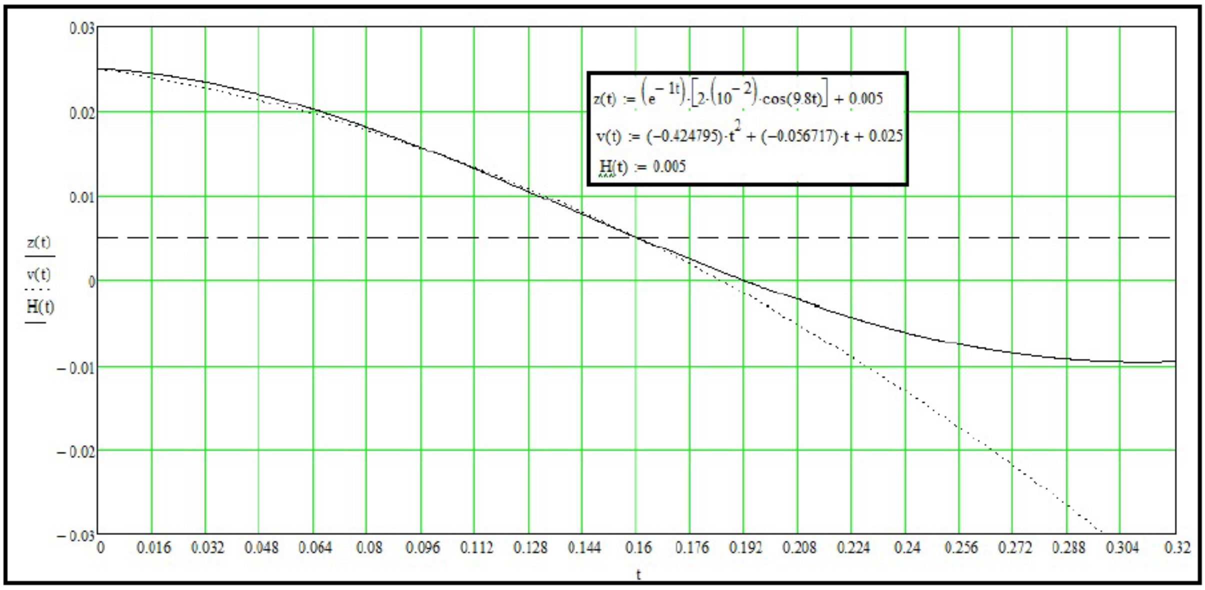

Figure 8-difference between the real data and quadric approximation function

Double differentiation of equation 6 in the distance between (θ_0-θ_2) can lead us to achievement of rotational acceleration in magnetorquer movement and as a result we are able to calculate one the unknowns in equation 4 (equation7).

$$\ddot{\theta} = \alpha = 2A \qquad (7)$$

In such approach, two more unknown elements remains, which can be obtained via calculating a system of two equations by the data that has been recorded by sensors. The mentioned calculations are based on equation 4 applied to design the testing algorithm for measuring the magnetic dipole and also magnetic torque.

5. Testing algorithm and computer program in measurement of M, K, and T magnetorquer vectors via kosar 100

For a facile usage of kosar 100, we managed and designed a computer program. First this program will receive the desired magnitude and magnetic field direction from user (θ_1 in figure 1) and the magnitude of Earth's magnetic field from magnetometer, calculate required electric current to compensate Earth's magnetic field and produce desired magnetic field and drive it. In the next step, it will receive the data that has been recorded by vision processor sensor and also the specifications of the testing magnetorquer. Eventually, it will measure M, K, and T vectors as an output factors and announce these to the user. This process will describe in this section.

5.1. Testing algorithm for determination of M, K, and T vectors in magnetorquer

Firstly, Kosar 100 system was installed in a manner that the axes of its rings were exactly in the direction of geographical axes. And also the sensors were installed in the way to have the east axis as the zero degree axis. (θ=0 in Fig. 3). Then the magnetorquer was placed in the system and reach the equilibrium in the direction of θ_0 as a result, we not only observe the desired currents in rings of simulator field, but also an electric current of 1 ampere is drived in magnetorquer. The timer started to work till the time the magnetorquer reaches the equilibrium point at θ_2. The operator has recorded three angular conditions with the time that takes to reach the positions between θ_0 and $\theta_2$via a sensor. Afterwards, we use the data and specifications of magnetorquer and simulated magnetic field as input for the computer program and consequently, measure T, M and K vectors.

5.2. Algorithm of computer program in determination of T, M, and K vectors

Firstly, the driver program takes three angles and times as input, subsequently; via Newton's method we are able to extract the coefficients of second order equation (equations 8- 15). Via the extracted coefficients, the rotational acceleration will be calculated and put in equation 4, along the moment of inertia.

$$\theta(t) = \theta(t_0) + (t - t_0)F[t_0, t_1] + (t - t_0)(t - t_1)F[t_0, t_1, t_2] \quad (8)$$

$$F[t_0, t_1] = \frac{\theta(t_1) - \theta(t_0)}{(t_1 - t_0)} = b \quad (9)$$

$$F[t_0, t_1, t_2] = \frac{\theta(t_0)}{(t_0 - t_2)(t_0 - t_1)} + \frac{\theta(t_1)}{(t_1 - t_2)(t_1 - t_0)} + \frac{\theta(t_2)}{(t_2 - t_0)(t_2 - t_1)} = c \quad (10)$$

$$\theta(t_0) = a \quad (11)$$

$$\theta(t) = ct^2 + [b - (t_0 + t_1)c]t + [a - bt_0 + ct_0t_1] \quad (12)$$

$$zt0 = [a - bt_0 + ct_0t_1] \quad (13)$$

$$zt1 = [b - (t_0 + t_1)c] \quad (14)$$

$$zt2 = c \quad (15)$$

Also, M and K vectors obtained through 16 and 17 equations.

$$M = \frac{2IC(\theta_0 - \theta_2)}{B[(\theta_2 - \theta_0)\, sin(\theta_1 - \theta_0)]} \quad (16)$$

$$K = \frac{2IC[sin(\theta_1 - \theta_0) - sin(\theta_1 - \theta_2)]}{[(\theta_2 - \theta_0)\, sin(\theta_1 - \theta_0)]} \quad (17)$$

The value of torque obtained from the program, which is generated on every moment in magnetorquer via equation 18, furthermore, the program obtained the maximum value via equation 19.

$$T_{magnetorquer} = I\, 2C + K(\theta - \theta_0) \quad (18)$$

$$T = M * B \quad (19)$$

6. Experimental explanation and results of the magnetorquer NSFe-1 examination

Magnetorquer NSFe-1 constructed via Nano technology (figure 9) Space Research Laboratory of Aerospace Faculty–Khajeh Nasireddin Toosi University of Technology. Under some structural conversions, magnetorquer core mass is decreased and it's magnetic dipole increased. Such magnetorquer is amplified for Nano and micro satellites purposes and will be tested by kosar 100.

Figure 9- NSFe-1 Nano magnetorquer without cover

Physical characteristics of such systems are shown in the Table 1.

Table 1- Physical characteristics of NSFe1

Quantity	Symbol	Sign	Value
Diameter of magnetorquer	R	mm	14.25
Mass of magnetorquer	m	gr	52.9
magnetorquer length	L	mm	58.82
Moment of inertia	I	$Kg.m^2$	$1.5252*10^{-5}$
Number of turns	N		95
Electric current in magnetorquer	I	A	1

7. Experimental explanation and results

The designed magnetic field magnitude, which will generate by kosar 100 simulator in the direction of 45 degree from eastern geographical axis, will equal to 1.0 gauss. Via the driver program, 0.87 ampere electric current in the small ring and 1.32 ampere electric current in big ring has been calculated and drived and the desired magnetic field will be generated. After generation of desired current in the ring and also testing the magnetorquer NSFe-1, three angles and times recorded via the sensors which are shown below tables 2,3:

Table 2- essential parameters in test process

Parameter	Sign	Value(deg)	Transition time(s)
Torsional torque stability angle	θ_0	58.9	2.25
Predicted stability angle	θ_1	45	2.3

final stability angle	θ_2	53.15	2.45

Table 3-final result of NSFe1 test by use of Kosar100 procedure

Parameter	Symbol	Unit	Value
Magnetic dipole	M	$A.m^2$	1.366670
spring constant	K	N.m/rad	$1.3408836*10^{-4}$
Maximum torque	T	N.m	$1.3666700*10^{-4}$

In table 4 magnitude of magnetic dipole and maximum torque vectors have been mentioned which specified by use of Kosar100 and J. Lee procedures and electromagnetic equation (equation3).

Table4-Comparision of final result of NSFe1 magnetorquer test

Parameter	Symbol	Unit	Value Kosar100	Value J. Lee	Value Electromagnetic equation
Magnetic dipole	M	$A.m^2$	1.370623	1.577683	1.421336
Maximum torque	T	N.m	$1.370623*10^{-4}$	$1.577683*10^{-4}$	$1.421336*10^{-4}$
Error	---	---	≈+0.04	≈+0.11	0.0

If we accept that equation3 specified accurate result, table4 shows that kosar100 procedure has less error than J. Lee procedure.

8. Conclusion

For the purpose of investigation and extraction the control relations that rule the space systems which use the magnetic control system and in the order of investigation and extraction the features of control elements in such systems, we put building a magnetic field simulator (kosar 100) system, in the Space Research Laboratory of Aerospace Faculty – University of Khajeh Nasireddin Toosi (KNTU). Such system is investigated in a postgraduate thesis.

In the purpose of verifying the magnetic dipole and control torque, as a magnetic element, we should test them via kosar100 system. Since a direct approach in for such measurement, does not exist, therefore we test diversity of methods (with diversity basics). Kosar 100, have the advantage of making the earth's magnetic field zero. Also it will decrease human error. Consequently, we have a method with high precision. In this article we described Experimental algorithm, mathematical- physical basis and a computer program, which are applied in determination of magnetorquer features (torque and magnetic dipole). Eventually we present characteristics and results of the tested magnetorquer NSFe-1, which is constructed via nanotechnology.

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