Abstract—Magnetic effects of satellites should be carefully studied starting from the design phase by creating a stringent magnetic cleanliness program. This program is required to maintain DC magnetic compatibility between units and reduce the interaction of satellite magnetic field with external magnetic field resulting parasitic torques. DC magnetic compatibility is especially important for satellites aiming scientific missions requiring sensitive magnetic equipment. Magnetic behaviour of satellites and its units can be understood by test and analysis. Although testing is the most reliable method to evaluate magnetic assessment quantitatively, analysis becomes the first step because of cost and time restrictions.

In this study, common analysis methods such as centred dipole approximation, multiple dipole modelling, spherical harmonics methods are discussed for their powerful and weak points. Centred dipole approximation will then be explained in more detail.

Index Terms—magnetic cleanliness, satellite, EMC

I. INTRODUCTION

Magnetically cleanliness of a spacecraft (S/C) is an important part of the design cycle. During this phase, orientation and selection of components should be carefully selected to follow the magnetic cleanliness policy. This process may be very critical in certain S/Cs especially if they have a specific magnetic mission as in NASA/JPL JUNO mission which carries a very sensitive magnetometer instrument performing measurements both in interplanetary cruise and in Jupiter’s magnetic field [1]. Not as crucial as a scientific S/C, similar cleanliness programs are necessary for Low Earth Orbit (LEO) satellites because they also carry a magnetometer for an accurate attitude control. Besides, the magnetic field of a satellite can interact with the field of Earth and therefore the satellite can experience parasitic torque. These effects must be taken into account for a safe mission. To ensure, satellites are subjected to design, test and analyzed from the perspective of magnetism.

II. MAGNETIC TESTING OF SATELLITES

Magnetic testing is performed to find the magnetic field level by S/C equipment on the point of sensitive magnetic field sensors more precisely, magnetometers. Some units may be the main reason for high levels of magnetic field such as stepper motors, solar array actuator motors, travelling wave tube amplifiers (TWTA), radio frequency (RF) components and so on. Previous studies estimated that even 10 meters away from S/C, there was a significant field level where the magnetometer is placed [1]. To reduce the risk, magnetic testing of S/C is the best choice if a test facility is available. This kind of test facilities is costly and time consuming. One of the few facilities in the world is shown in Fig. 1.

Fig. 1. Magnetic Test Facility MFSA with Rosetta Lander (courtesy of IABG), Reprinted from [2].

The facility in Fig. 1 and its analogues have the property of zeroing Earth’s field being naturally varying thanks to their closed-loop feedback systems. In addition to the determination of the permanent/induced magnetic moment of satellites and subsystems, they also simulate the magnetic environment of a spinning S/C. Furthermore, these facilities are used to calibrate magnetometers [2]. Instead of performing these tests, simulation methods can be chosen to reduce the cost, complexity and time. In the next section, analysis methods will be explained.

III. MAGNETIC ANALYSIS METHODS

A. Single Dipole Modelling

This approach is used to find the field level at an interested point by modelling each equipment as a single dipole magnet. Moreover, the S/C itself can be reduced to a single dipole magnet to ease the calculation parasitic interaction with external magnetic fields. The relation between magnetic field and magnetic moment can be written from [3] as below
\[ \vec{H} = \frac{1}{4\pi} \left[ \frac{3m \vec{R}}{R^5} - \frac{\vec{m}}{R^3} \right] \]  

where \( \vec{H}, \vec{m} \) and \( \vec{R} \) represent magnetic field in A/m, magnetic moment in A.m\(^2\) and distance vector between vector joining the dipole and observation point in meter, respectively. The magnetic induction \( \vec{B} \) is given in (2) and (3).

\[ \vec{B} = \mu_0 \vec{H} \]  

\[ \mu_0 = 4\pi \times 10^{-7} \text{ Henry} / \text{m} \]  

After some mathematical simplification, relation of orthogonal vector components of magnetic induction to their magnetic moment variables can be written as below

\[
\begin{bmatrix}
B_x \\
B_y \\
B_z
\end{bmatrix}
= \frac{1}{R^3} \begin{bmatrix}
3R_x^2 - R^2 & 3R_xR_y & 3R_xR_z \\
3R_yR_x & 3R_y^2 - R^2 & 3R_yR_z \\
3R_zR_x & 3R_zR_y & 3R_z^2 - R^2
\end{bmatrix}
\begin{bmatrix}
m_x \\
m_y \\
m_z
\end{bmatrix} 
\]  

where the absolute value of distance \( R \) equals to \( \sqrt{R_x^2 + R_y^2 + R_z^2} \).

During design phase, magnetic moment levels are requested from equipment suppliers. By using moment data of each unit, magnetic induction affecting on a magnetometer can be found and their vector summation gives the resulting magnetic induction without performing system level tests. Total magnetic induction value is then compared with the specifications of the magnetometer whether to degrade its functionality or not. If a unit has no data history at all, moment values from the literature about the unit can be accepted as an input. If an exact value is necessary, unit level magnetic field tests which are more available than system level test facilities can be performed. A suitable unit level test center is given in Fig. 2.

Aside from magnetometer induction level estimation, another important output of this method is to find the parasitic torque which can be problematic for attitude and orbit control system (Aocos). Parasitic (perturbation) torque is found by vectorial product of magnetic moment and magnetic induction in the same geometrical reference as in (5).

\[ \vec{T} = \vec{m} \vec{B} \]  

More precisely, torque calculation is shown in (6).

\[
T_x \hat{x} + T_y \hat{y} + T_z \hat{z} = 
\begin{bmatrix}
\hat{x} & \hat{y} & \hat{z}
\end{bmatrix}
\begin{bmatrix}
m_x & m_y & m_z \\
T_x & T_y & T_z
\end{bmatrix}
\]

Magnetic field levels on an orbit can be found easily from International Geomagnetic Reference Field (IGRF) model (Fig. 3). According to this model, at 500 km altitude over Turkey in August 2015, magnetic field components, \( B_x, B_y \) and \( B_z \) are estimated as -7426, -19407 and 30474 nT, respectively according to the satellite body coordinate system.

Assuming that magnetic moment levels of a satellite are 5, 3 and -3 A.m\(^2\) in \( x, y \) and \( z \) directions respectively, the torque is found as 111 μN.m. The amount of torque is then taken into account in AOCs. A high value of torque can bring an extra burden on reaction wheels being undesirable in general. There are several ways to reduce the torque by taking some measures. For example, certain units can be placed in a way that their magnetic moments cancel each other. This approach works well especially at solar panels being the most significant source of magnetic fields due to large currents. With proper interconnection, those parasitic fields can be reduced to minimum. Material selection and cable routing design are another precautions to take.

Measurement of equipment under test (EUT) magnetic moments for this model can be done by simple “Six Points Method”. This method is not the most precise but the simplest
way to estimate the magnetic moment of EUT. Moment levels are deduced from 6 different measurements as in Fig. 4. The dipole is assumed to be at the center and the magnetic field is defined as positive when pointing from the EUT towards the magnetometer. In (7), x component of magnetic moment calculation is shown and the other components are found similarly [2].

\[ m_x = 5r^3 \left( \frac{B_{z1} \mu T - B_{x1} \mu T}{2} \right) \]  

(7)

B. Multiple Dipole Modelling

The method in the previous section was to replace the entire unit/satellite by only one dipole which might not be precise enough for some applications. Multiple Dipole Modelling (MDM) approach uses near field measurements for the construction of a theoretical multiple dipole image test object as its first developer says in [5]. To do that, a more precise measurement technique than “Six Points Method” is set up. This test is a kind of rotational rotational magnetic measurement with enough angular steps. The setup is depicted in Fig. 5. Using measurement data, an initial guess is done to form multiple dipoles’ positions and numbers. Initial guess is modified until calculation and measurement results match. This method is well defined in [2, 5, 6]. The main advantage of MDM method is relatively easier physical interpretation of dipole positions and moment with a drawback of lacking a unique solution [2]. There is well-known software using this method to estimate DC magnetic EMC levels [7].

C. Spherical Harmonics Modelling

Spherical Harmonics Modelling (SHM) is a very common technique for engineers and scientists working at the field of geomagnetism to predict Earth’s magnetic field at any point which cannot be measured. It is based on finding a magnetic potential by using Schmidt quasi-normalized associated Legendre function being conventional in geomagnetism. The detail of this method is out of scope of this paper, so more detail can be found in [2] for further information. Regarding test setup, it is based on a spherical measurement as it was rotational for MDM and “Six Points Method” for single dipole modelling (SDM). Measurement setup can also be seen in Fig. 6 and it has to maintain regular coverage of a sphere.

IV. CONCLUSION AND FUTURE WORKS

In this study, after giving an introduction about magnetic cleanliness, common analysis methods such as centred dipole approximation, multiple dipole modelling, spherical harmonics methods were introduced and discussed in terms of their inputs i.e. measurement needs and accuracy. Centred dipole approximation was explained in more detail. An example torque calculation was performed.

With the help of methods, realistic torque calculations will be estimated. Different methods will be compared to find the accuracy levels of methods. Optimization techniques will be applied for method improvement.
ACKNOWLEDGMENT

The authors would like to thank to Mr. Kagan Ataalp for providing accurate magnetic field data and to Dr. Kutlay Aydin for supporting this work.

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