Passive Micro Vibration Isolator Utilizing Flux Pinning Effect for Satellites

Takuma Shibata* and Shin-ichiro Sakai**
*Department of Space and Astronautical Science, The Graduate University for Advanced Studies, SOKENDAI
3-1-1, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan
**ISAS/JAXA
3-1-1, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan
E-mail: ts761943is.as@ac.jaxa.jp

Abstract. Information related to the origin of space and evolution of galaxy can be obtained using the observation satellites. In recent years, high pointing accuracy is demanded for getting more detailed data about distant stars and galaxies. As a result, vibration isolators that consist of a main structure and a TTM (Tip Tilt Mirror) have been adopted for observation satellites. However, cutting the low frequency vibrations off passively with the conventional methods is difficult. A vibration isolator that uses pinning effect is proposed for solving this problem. The pinning effect is acquired by cooling the type-II superconductor below the critical temperature and it generates a pinning force to maintain the relative distance and attitude between a type-II superconductor and a material that generates magnetic flux. The mission part and the bus part of the satellite are equipped with superconductors and permanent magnets and these parts perform short distance formation flight by applying the effect. This method can cut vibrations from low to high frequency bands off passively. In addition, Meissner effect can prevent collision of the mission and bus parts. In order to investigate the performance of this system, experiments and simulations are carried out and the results are discussed.

1. Introduction
1.1. Background
Diverse information about galaxies and planets far from the Earth can be acquired using the observation satellites. High pointing accuracy has been demanded for obtaining information about further planets and galaxies in recent years. Disturbance is a problem when these satellites must observe with high pointing accuracy. The vibrations generated by the reaction wheels or the refrigerator in the bus part are some of these disturbances and the observed data blurs if these vibrations are transmitted to the mission part (Fig.1). Different methods that use the Tip Tilt Mirror (TTM)[1] and Sterwart platform[2] have been researched for restraining the influence of these vibrations. However, these methods hardly cut the vibrations of low frequency band off passively. Therefore, If an actuator, which is used for these conventional methods, is broken the observation satellite can not achieve high pointing accuracy. Besides, observation satellites that have both a primary and secondary mirror do not only experience the effect of vibrations but also the heat transfer. The heat is produced by equipments in the bus part and transmitted to the mission part through the conventional vibration isolator. This effect decreases the pointing accuracy as the heat strain causes vibration and deformation of the mirrors. In this paper, the micro vibration isolator utilizing the flux pinning effect is proposed.
1.2. Flux pinning effect

Flux pinning effect occurs between a type-II superconductor and a material that produces magnetic flux (e.g. permanent magnet). The state of the superconductor changes from the normal conducting state to the superconducting state by cooling below the critical temperature. In this case the superconductor gains two properties that are called perfect conductivity and perfect diamagnetism. The perfect conductivity is the effect that the internal resistance in a superconductor can be approximated to zero. The perfect diamagnetism, which is also called the Meissner effect, is also generated by the cooled superconductor. The effect has property that the induced current prevents external magnetic flux intruding the superconductor. Currents that are named the shielding currents are induced on a superconductor by Lenz’s law as a magnetic flux generating material approaches. In addition, the magnetic flux is repelled out of a superconductor by cooling below the critical temperature since Lorentz force is generated between the current and magnetic flux(Fig.2), even if the magnetic flux penetrates through a superconductor that is in normal conducting state. However, if a type-II superconductor has impurities and cracks, it does not repel out magnetic flux. These impurities and cracks in the type-II superconductor are not superconducting and hold the normal conducting state when the type-II superconductor is in superconducting state. Therefore, the flux is pinned in the impurities and cracks and pinning force competes with Lorentz force. Pinning force helps to maintain the relative distance and attitude between a type-II superconductor and magnetic flux generating material passively. The force can be approximated by a spring and damping force regarding the infinitesimal displacements.

Because of these reasons, many researches about devices with magnetic flux pinning effect (e.g. quake-free device[3] and transport mechanism[4]) have been conducted. In addition, this effect has been researched for formation flight technology where a number of satellites perform their mission by flying in formation. Electro-magnetic force [5], Coulomb force [6], Lorentz force [7] and pinning force [8] have been studied for controlling relative attitude and distance between the satellites since these formation flight methods have certain advantages compared with the formation flight using the thrusters.

Figure 1. The influence of the vibrations from the bus part
2. The proposed micro vibration isolator

2.1. The mechanism of the proposed micro vibration isolator

The proposed micro vibration isolator is composed of permanent magnets, electro-magnets and type-II superconductors (Fig.3). In this study, our aim is to develop a micro vibration isolator that can cut the vibrations from low to high frequency band off passively using the formation flight technology and flux pinning effect. Permanent magnets and electro-magnets are mounted on the bus part and the mission part is equipped with type-II superconductors. The mission and bus parts of the satellite that has the proposed micro vibration isolator performs a short distance formation flight. The relative distance and attitude are maintained by flux pinning effect. Moreover, collision of these parts is prevented by Meissner effect. The effect works when a superconductor cooled below the critical temperature, and the type-II superconductor repels out external magnetic flux. Thereby, the repulsive force is generated between the type-II superconductor and the permanent magnet which are getting closer. Pinning force can be approximated by the spring damping force and is easy to model. Due to the flux pinning effect, this isolator enables cutting off the low frequency vibrations without active control.

Furthermore, the proposed micro vibration isolator can control the attitude of the mission part using the Meissner effect that we can control by the electro-magnets. Repulsive force is
generated by applying magnetic flux to the type-II superconductors and changes the attitude of
the mission part. Controlling the mission part enables aligning the observation direction of the
mission part with the observed target.

This proposed micro vibration isolator can resolve the problem of not only the vibration
but also heat strain since the mission and bus parts are not connected with a structure as in
a conventional vibration isolator. Besides since the method is passive any measures against
actuator failure is not necessary.

2.2. Numerical model for the proposed micro vibration isolator
Frozen image model is used as a numerical model for calculating the pinning force that is
generated between a type-II superconductor and a permanent magnet. This model proposed by
Alexander Kordyuk[9] can be used assuming that the type-II superconductor is huge compared
to the permanent magnet it is levitating on. In addition, a permanent magnet is approximated
by magnetic dipole in this model. The pinning force is calculated using two images, which are
called the frozen image and mobile image (Fig.4). These images are generated in the type-II
superconductor when the superconductor is cooled below the critical temperature. Each image
has magnetic moments that are same with the moment of the permanent magnet in magnitude
but with different directions. Those magnetic moments is represented by following equation:

\[ \vec{M}_{\text{mag}} = \vec{M}_f = -\vec{M}_m. \]  (1)

\( \vec{M}_{\text{mag}}, \vec{M}_f \) and \( \vec{M}_m \) is magnetic moment vector of a permanent magnet, a frozen image and a
mobile image respectively. Magnetic dipole vector direction of mobile image is in line symmetry
with respect to type-II superconductor’s surface. Furthermore, this image moves with motion
of the permanent magnet. In contrast, frozen image has magnetization vector whose direction
is opposite of the mobile image and keeps the initial position even when the permanent magnet
moves.

The pinning force as well as the torque can be calculated as the total force generated between
the permanent magnet and each images. The method for calculating the force and torque are
formulated in [10]. Similar expressions are used for calculating the pinning force and torque. The

![Figure 4. Frozen image model](image-url)
force and torque generated between each images and the permanent magnet can be determined with the following expressions:

\[ F_{f,m} = \mu_0 \nabla (H_{f,m} \cdot M_{mag}), \]  
\[ T_{f,m} = M_{mag} \times \mu_0 H_{f,m}. \]  

The pinning force \( F_{f,m} \) and torque \( T_{f,m} \) can be calculated using the magnetic moment \( M_{mag} \) and magnetic field \( H_{f,m} \) generated by frozen and mobile images. Here, subscript \( f \) or \( m \) means the value is generated between the frozen or mobile image and the permanent magnet. Magnetic field of each images at the position of the permanent magnet is given with the following expression:

\[ H_{f,m} = \frac{1}{4\pi r_{f,m}^3} \left\{ -M_{f,m}r_{f,m} + \frac{3(M_{f,m} \cdot r_{f,m})}{r_{f,m}^2} r_{f,m} \right\}. \]  

Here, \( r_{f,m} \) is the distance vector from images to the permanent magnet and the images have magnetic moment vector \( M_f \) and \( M_m \). Finally, pinning force and torque between the permanent magnet and the type-II superconductor are obtained by

\[ F_{lev} = F_f + F_m, \]  
\[ T_{lev} = T_f + T_m. \]  

### 3. Validation of frozen image model by an experiment

#### 3.1. Equipment for measuring the pinning force

The sizes of the permanent magnet and the type-II superconductor (Fig.5) used in the experiment are given in Table.1. The measurement experiment using the equipment given in Fig.6, Fig.7 was carried out for validation of the frozen image model. The equipment consists of mainly

|                  | \( \text{Radius}[\text{mm}] \) | \( \text{Height}[\text{mm}] \) |
|------------------|-------------------------------|------------------------------|
| Neodymium magnets| 10                            | 15                           |
| Type-II superconductor| 12.5                        | 12                           |

Figure 5. Permanent magnet and type-II superconductor used in measurement experiment
aluminum and acrylic so as to magnetize the equipment. The permanent magnet is connected to the spring balance by string and attached to the aluminum circle plate. The displacement is measured by a laser rangefinder ‘LK-G 405 and LK-G3000’ by Keyence, and the pinning force is measured by the spring balance when the permanent magnet moves from the initial position. The pinning force was measured three times for which the initial distance between the permanent magnet and the type-II superconductor are 6.5[mm], 7.5[mm] and 8.5[mm], respectively.

**Figure 6.** The measurement equipment

**Figure 7.** Illustration of the measurement equipment

### 3.2. Calculating the permanent magnet’s magnetization

For understanding the validation of the numerical model, the magnetization of the permanent magnet was determined by measuring the magnetic field. The derived magnetization is substituted for frozen image model and the model is compared with the experimental results.

A sheet that was marked with a line at every 5.0[cm] from initial point to 30[cm] was put on the table. The permanent magnet was put at the initial point and the magnetic field was measured at each points by the probe of ‘Lake shore high cost performance gauss meter 421 type’ (Fig.8). After measuring the magnetic field, the magnetization of the permanent magnet was estimated using the least-squares method and the measured magnetic field.

Magnetic moment of the permanent magnet was estimated by the least-squares method. Magnetic field of only z direction(normal direction to the permanent magnet’s plane) can be simplified using the following expression:

$$H_z = \frac{M_z}{2\pi z^3}. \quad (7)$$

Let $\frac{1}{z}$ approximates $Z$. Then Eq.7 is rewritten as the following expression:

$$H_z = \frac{M_z}{2\pi} Z^3. \quad (8)$$

The sum of squares to be minimized is represented using the above equation (8) as follows:

$$E = \sum_{i=0}^{n} (2\pi H_{zi} - M_z Z_i^3)^2 = 0. \quad (9)$$

And, the partial derivation of $E$ can be written as

$$\frac{\partial E}{\partial M_z} = -2 \sum_{i=0}^{n} (2\pi H_{zi} - M_z Z_i^3) Z_i^3 = 0. \quad (10)$$
Figure 8. Lake shore high cost performance gauss meter 421 type

Magnetic moment can be solved using the Eq.(10) as

\[ M_z = \frac{2\pi \sum_{i=0}^{n} H_i Z_i^3}{\sum_{i=0}^{n} Z_i^6}. \]  

(11)

Then, magnetic moment \( M_z \) is determined as \( 3.49[Am^2] \), and the magnetization \( m_z \) becomes \( 7.41 \times 10^5[A/m] \). The comparison of the measured magnetic field with magnetic field calculated using the magnetic moment is given in Fig.9. Regarding this result we may say that the magnetic moment is almost correct. Hence, the magnetization can be represented with the numerical model.

![Figure 9. Measured and calculated magnetic field](image)

3.3. Measurement results compared with the frozen image model

The results for the measured pinning force are given in Fig.10, Fig.11 and Fig.12. Initial distances are 6.5[mm], 7.5[mm] and 8.5[mm] respectively. The measured pinning force is similar in all three cases. The force that is averaged over three times is compared with the numerical results (Fig.13). In Fig.13, Sim and EX express a simulation and an experimental results respectively. The pinning force calculated by numerical model almost matches with the measured pinning force. Thus, this model can be used for the proposed micro vibration isolator.
4. Numerical results

4.1. Required pinning force and torque for cutting off low frequency vibrations

It is assumed that the satellite has a mission and bus part each with a 500[kg] mass. Height of the mission part is 6.0[m] and the bus part is 2.6[m]. Radius of both mission and bus part is 1.9[m](Fig.3). The low spring coefficient is demanded for cutting the low frequency vibrations off. For cutting the vibrations at 0.1[Hz] band off passively, 0.2[N/m] spring coefficient is necessary. In addition, the satellite conducts a mission on halo orbit at L2 point of Earth-sun system. Solar radiation pressure affects the satellites predominantly on the halo orbit at L2 point. The solar radiation pressure can be evaluated using the following expression[11]:

\[ T_{sp} = P_s A_m H_m (1 + q) \cos(i) \]  

(12)

\( P_s \) is a solar radiation coefficient and the value is \( 4.617 \times 10^{-6}[N/m^2] \). \( A_m \) is the effective area. \( H_m \) is the length between the center of gravity and the point of sun pressure. \( q \) is the reflection coefficient and \( i \) is the angle between the effective area and the direction of sun pressure. In case of estimating the maximum torque and force by sun pressure, \( q \) is 1 and \( i \) is \( 0^\circ \).
The maximum force by solar radiation pressure can be calculated using difference of effective area between the mission and bus part. The maximum torque is calculated supposing that only the mission part rotates around the center of the bottom. In this case, the force and torque by solar radiation pressure are $1.19 \times 10^{-4} [N]$, $1.26 \times 10^{-3} [Nm]$, respectively.

If the pinning force and torque are larger than the solar radiation pressure, the relative distance and attitude between the mission and bus parts can be maintained. In this research, the possibilities for the proposed micro vibration isolator, which can cut the vibrations at 0.1[Hz] band off and also maintain the relative distance and attitude, are discussed.

4.2. Analysis results by frozen image model

Pinning force and torque are simulated using the frozen image model for discussing the possibilities of the proposed micro vibration isolator. Low spring coefficient is needed for cutting the vibrations of low frequency band off between the mission and the bus part of the satellite. For cutting the vibrations at 0.1[Hz] band off, a spring coefficient of 0.2[N/m] must be achieved. In numerical analysis, the mission part moves along $+z$, $-z$ and $x$ axes in addition to the rotation around $x$ and $y$ axes (Fig.14). The proposed micro vibration isolator has one permanent magnet with radius 5[cm], height 5[cm], and magnetization $7.41 \times 10^5 [Am]$. The initial distance between the mission and bus parts is changed so that the spring coefficient becomes 0.2[N/m]. In case of using one permanent magnet, the initial distance is 0.475[m].

The results for the pinning force are shown in Fig.15, Fig.17 and Fig.19 when the spring coefficient is as given in Fig.16, Fig.18 and Fig.20, respectively. If the mission part moves along $+z$ axis from the initial point, pinning force increases as in Fig.15. The force in $+z$ direction gets the maximum value of -0.011[N] at 0.65[m] from the initial position. However, pinning force decreases as the mission part passes through 0.65[m] from the initial point. Hence, there is a possibility that the satellite separates if the external force is bigger than the pinning force of 0.011[N]. However, it is considered that the distance can be maintained because the force of solar pressure is sufficiently smaller than the pinning force.

Fig.17 is the force in case the mission part moves in $-z$ direction. The force increases exponentially when the mission part approaches to the bus part. This repulsive force is caused

Figure 14. The satellite with the proposed micro vibration isolator in three axis
by Meissner effect. The collision of the mission part and bus part can be prevented by this effect.

As to the force in x direction, the maximum value of the force is 0.023[N] at 0.4[m] from the initial position (Fig.19). In this case, not only the force in the x direction but also in the z direction is generated. The z direction force is caused by Meissner effect. The influence of the force in z direction must be considered for maintaining the relative distance and keeping high pointing accuracy. The x direction spring coefficient is 0.1[N/m] at initial point in Fig.20, therefore the low frequency vibrations can be cut off sufficiently.

When the mission part rotates around x and y axes, the same torque is generated (Fig.21, Fig.22). However, the torque about z axis is not generated if the mission part rotates around z axis. The flux pinning effect allows the permanent magnet to rotate with low energy loss on the type-II superconductor if the change in the applying magnetic field is very small. Hence, when the proposed micro vibration isolator is mounted on the observation satellites, two of the permanent magnets and type-II superconductors are needed at minimum.

The calculated force and torque values as a result of the analyses are very small. However, the external force of solar pressure is in the order of -4 on halo orbit at L2 point, so these...
pinning force can maintain the relative distance between the bus and mission part. Regarding the torque, z axis torque is not generated. Therefore, more than two permanent magnets and type-II superconductors are necessary for preventing the mission part from rotating around z axis.

5. Conclusion
The passive micro vibration isolator using the flux pinning effect was proposed in this paper. The frozen image model was used for understanding the pinning force and torque generated between the bus and mission parts of the satellite. The pinning force can maintain the relative distance between the bus and mission parts on halo orbit at L2 point. However, regarding the relative attitude, torque around z axis can not be generated since the magnetic flux, which applies to the type-II superconductor, does not change. Since the pinning force is generated by the gradient of magnetic field, torque around z axis is not generated. It is needed that permanent magnets and superconductors are mounted on the mission and bus parts. The pinning force and torque must be calculated in case of using the permanent magnets and type-II superconductors. In addition, damping coefficient also must be calculated for cutting the low frequency vibrations.
off. However, in our case, we assume the damping force by the flux pinning effect is small. We need to have an eddy current damper[12][13] or shunt damper[14] to acquire the damping force. Designing the attitude control system of the mission part is future work in this research.

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