Dynamic Analysis of Three Dimensional Reaction Wheel using Finite Element Method (FEM)

Sho Ohtani(The University of Tokyo), Jun’ichiro Kawaguchi, Yuichi Tsuda, Takanao Saiki, Yoji Shirasawa(JAXA), Keita Tanaka and Ryo Jifuku(The University of Tokyo)

Abstract: This paper shows analysis of Three Dimensional Reaction Wheel (3DRW) behavior using Finite Element Method. 3DRW applies magnetic force to float itself in constant position and rotate to produce desired torque. Compared to regular reaction wheel, 3DRW has two advantages; no contacting points and smaller size (and mass). Due to these two features, 3DRW is applied to nano-satellites which must meet severe regulation regarding size and mass. Besides some experimental achievements, I executed several simulations using ANSYS, software applying finite element method, to demonstrate that simulation results are well fitted to theory and experimental ones. Furthermore, simulation takes a key part in demonstrating pre-simulation of proposed experiments.

有限要素法を用いた 3 次元リアクションホイール挙動解析

大谷翔(東京大学)，川口淳一郎，津田雄一，佐伯孝尚，白澤洋次(JAXA)，田中啓太，地福亮(東京大学)

摘要: 3 次元リアクションホイールとは、磁場によって球体を浮上・回転させて 3 軸制御を行う姿勢制御装置である。これについて、有限要素法解析ツール ANSYS を用いて動電磁場解析を行う。そのシミュレーション結果を基にこれまで実施された実験データおよび先行研究と比較、その妥当性を検証する。さらに未実験段階にある球殻モデルを用いたシミュレーションを実施し、より実用面での利用を目指す。

1. Introduction

Reaction wheel takes a key role in controlling spacecraft in modern space developments. However, it has several weak points such as huge mass and required number of devices for one spacecraft. Therefore, it is not suitable for world-trend small satellites whose requirements are severer than bigger ones. Moreover, it has mechanical contacts which often cause fatigue defects. In order to tackle with these problems, we aimed to realize non-contact three-dimensionally controllable reaction wheel by applying magnetic field to it. In this study, I analyzed its behavior using ANSYS, finite element analysis tool, in order to demonstrate how reaction wheel behaves before experiments.

2. Three Dimensional Reaction Wheel Behabior[1] and Application of Finite Element Method

Fig.1(right) shows conceptual design of Three Dimensional Reaction Wheel. Its behavior is separated into two steps: floating and rolling control. First, the rigid ball floats due to magnetic field executed from electric magnet. Next, the rigid ball receives another magnetic field for rolling control from three axes. While conventional reaction wheels must be deployed at least three in total to function, three dimensional wheels need only one to be deployed to control fully. Fig.2 shows formation of electro magnets. Each component produces magnetic field to apply rolling magnetic field to the rigid ball. Thus, eddy current is produced on the surface of the ball. Then finally, torque for rolling the ball is produced by interaction between eddy current and magnetic field.

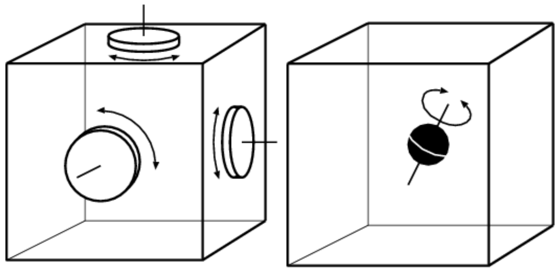


Fig.1 Three Dimensional Reaction Wheel

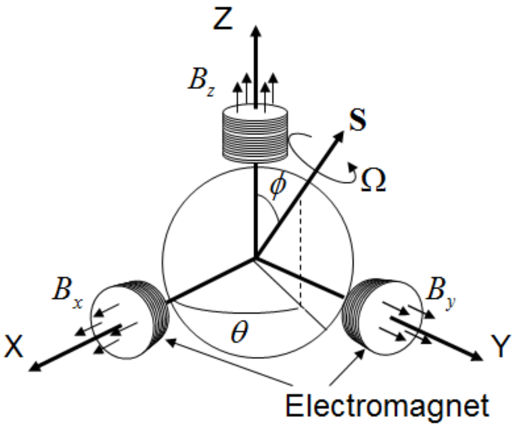


Fig. 2 Formation of electro magnets

ANSYS applies Maxwell equations below for electromagnetic analysis using finite element method.

$$\mathrm{rot}\mathbf{H} = \mathbf{J} + \frac{\partial \boldsymbol{D}}{\partial t}$$

$$\mathrm{rot}\mathbf{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\mathrm{div}\mathbf{B} = 0$$

$$\mathrm{div}\mathbf{D} = \rho$$

B: magnetic flux density[T]

E: electric field[V/m]

H: magnetic field[A/m]

J: current density[A/m^2]

D: electric flux density[C/m^2]

ρ: electric charge density[C/m^3]

3. Theory Model Assumptions

I consider assumptions below to calculate theoretical values.

- Magnetic field rotates around the rigid ball.（ideal rolling magnetic field）
- Magnetic flux straightly penetrates any material.（Fig. 3）

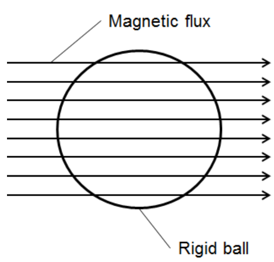


Fig. 3 Theory Assumption of Magnetic Flux Distribution in rigid ball

In order to get analytical value of cylindrical model, I use following equation.

$$dF_\theta = -\sigma r^2 \omega cos^2\theta \ \mathrm{d\theta drdz}$$

dF_θ: Tangential force [N]

σ: Electric conductivity [S/m]

ω: Angular velocity [rad/s]

θ: Angle from x axis [rad]

r: radius [m]

z: height [m]

4. Ground Experiment using Aerial Pressure

In order to consider magnetic float and rolling control independently, we used floating equipment[1)] using aerial pressure instead of magnetic float. In this paper, I only consider rolling control applying magnetic field.

5. Setting

Due to restriction of education version software, I made two-dimensional model. Simulation setting matches to actual position and size of the experimental model.

5.1 Magnetic flux distribution in cylinder

In simulation, magnetic fields from two axes are applied to infinite lengthy cylinder. Fig.3 and Fig.4 show two-dimensional model and mesh respectively. The rigid body is treated as cylinder to simulate magnetic behavior on circular section. It is assumed that density of magnetic flux is uniform regardless depth. Electromagnet model generate periodically-changing magnetic field. Its norm is approximately5000 A/m. Results are showed in the form of magnetic flux distribution.

Previous work[1)] treated rolling magnetic field ideally in its theoretical calculation. Additionally, it assumes that magnetic field straightly penetrates the rigid ball not considering its material property. However, rolling magnetic field is not ideal under the actual experiment condition. Therefore, magnetic field distribution is not perfectly simulated, and this research discuss its gap.

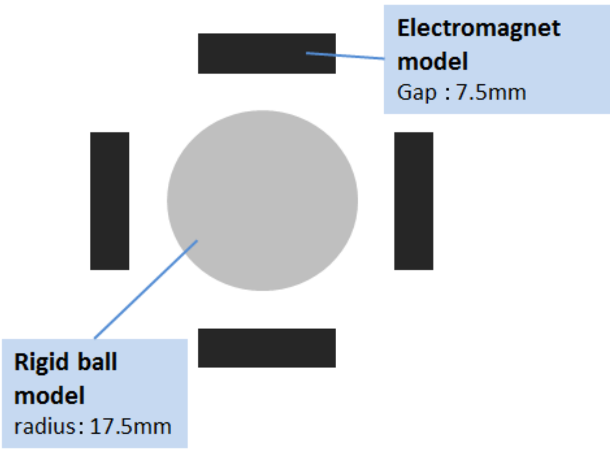


Fig.4　Model (infinite length)

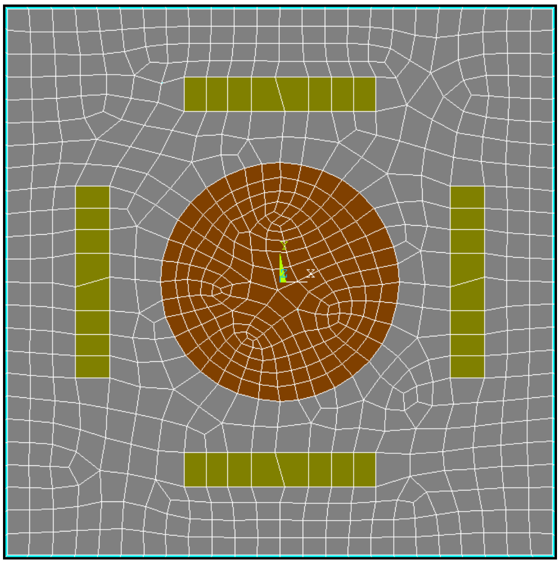


Fig.5　Mesh

Number of elements：749

Magnetic field norm：5000[A/m]

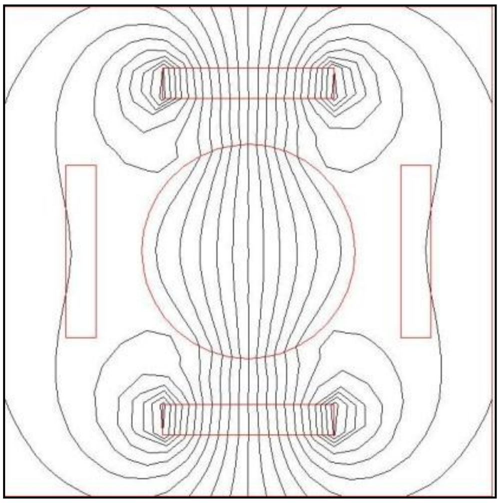
5.2 Gap between Theory Model and Simulated Torque Value

In theory model calculation, force and torque are constant regardless inserting angle of magnetic field due to its assumption. On the other hand, simulation results must show some gap between torque values subject to angle of magnetic field because theoretical assumptions do not fit actual environment. In the simulation, the gap between them van be measured. Model position and parameters are same as described in 4.1.

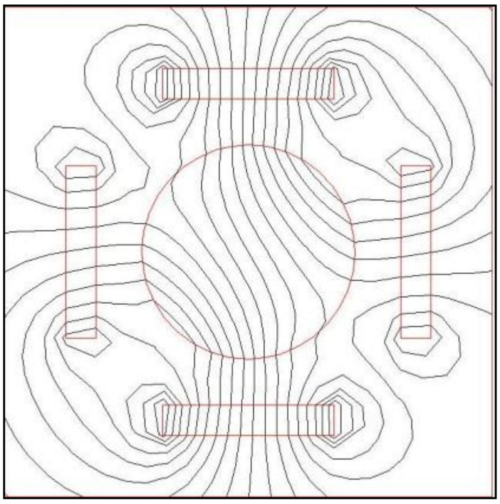
6.　Results

5.1 Magnetic Flux Distribution

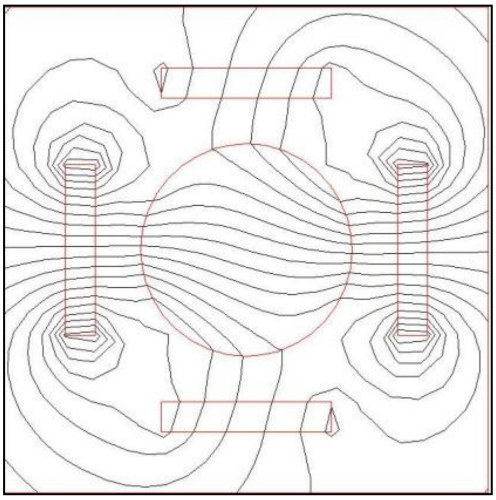
Fig.5 shows the magnetic flux distribution in the cylinder. The direction of magnetic field changes from 0 degree to 90 degree clockwise.



(0°　)



(30°　)



(60°　)

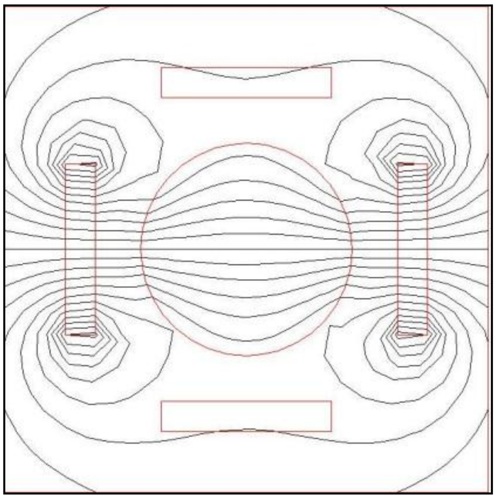

(90°)

Fig.6 Magnetic flux distribution in cylinder

The direction of magnetic flux rotates by controlling strength of magnetic field from the electromagnets. Compared to theory model, there are two characteristics which I did not considered when calculating theoretical values.

- Magnetic field does not go straight.
- Magnetic field disturbs due to gaps between electromagnets.

While straight-through magnetic field is applied in theory model, simulation results considering actual experimental condition does not show ideal distribution. The results indicate that ideal rolling magnetic field can not be achieved by controlling a number of electromagnets since they must consist of gap between themselves. In order to approach this problem, detailed torque calculation or increase in the number of electromagnets is necessary to decrease the level of disturbance.

5.2 Gap Coefficient between Theory and Simulation Models

Table.1 shows the results.

Table.1 results

Angle of magnetic field[°]	F_θ[N/m]	T[Nm/m]
0	6.14E-11	1.07E-12
30	6.20E-11	1.09E-12
60	6.20E-11	1.08E-12
90	6.12E-11	1.07E-12
Theoretical value	8.66E-11	1.52E-12

- Simulation values of 0 degree and 90 degree

Magnetic distributions of 0 degree and 90 degree are symmetry on x and y axis base, so both results behave similarly. Asymmetry of mesh caused tiny gap between these results. Compared to theoretical values, simulation results show smaller values because of the difference between theory model and simulation condition. Quantitatively, simulation results are about 29% less than theoretical one. As Fig.6 indicates, loss of magnetic field is considerable, causing to produce the gap.

- 30 degree and 60 degree

30 degree and 60 degree show the same behavior. This is because the strengths of magnetic field from two electromagnets are exactly same. Small gap between torque values are caused by asymmetry of mesh.

- 0-90 degree and 30-60 degree

This comparison shows the influence of disturbance caused by gaps between electromagnets. On average, simulation results are about 1.2% less than theoretical one.

7. Conclusion

This research shows magnetic field distribution can be simulated with infinite-lengthy cylinder model.

- Qualitatively, rolling magnetic field is simulated and shown in cylinder model.
- Qualitatively, torque gap between theory model with ideal rolling magnetic field and simulation results with actual experimental condition is calculated.

In reality, experiment should realize ideal rolling magnetic field or experimental model should be made more accurate by simulations.

Reference

1) 白澤洋次：3 次元リアクションホイールの性能解析と実験的検証，東京大学修士論文，2008
2) CYBERNET：ANSYS 低周波磁場解析ガイド ANSYS 12.1 版，2010」
3) 吉本成香（代表執筆者）：有限要素法ソフト ANSYS 工学解析入門 第 2 版，理工学社，2005