Attitude Control of Agile Spacecraft Using Momentum Exchange Devices

Hyunjae Lee*
Department of Aerospace Engineering
Korea Advanced Institute of Science and Technology, Daejon, Korea, 305-701

Shin-Je Cho**
Uninhabited Aerial Vehicle Group, Flight Control Division,
Korea Institute of Aerospace Technology, Daejon, Korea

Hyochoong Bang***
Department of Aerospace Engineering
Korea Advanced Institute of Science and Technology, Daejon, Korea, 305-701

Abstract

This paper is focused on designing an implementable control law to perform spacecraft various missions using momentum exchange devices such as reaction wheels(RWs) and control moment gyros(CMGs). A compact equation of motion of a spacecraft installed with various momentum exchange devices is derived in this paper. A hybrid control law is proposed for precision attitude control of agile spacecraft. The control law proposed in this paper allocates control torque to the CMGs and the RWs adequately to satisfy the precision attitude control and large angle maneuver simultaneously. The saturation problem of reaction wheels and the singularity problem of control moment gyros are considered. The problems are successfully resolved by using the proposed hybrid closed loop control law. Finally, the proposed hybrid control law is demonstrated by numerical simulations.

Key Word : Hybrid Control, Control Moment Gyros, Reaction Wheels, Singularity Avoidance

Introduction

The CMG cluster is a representative torque producing device for spacecraft attitude control. A single gimbal CMG contains a wheel spinning at a constant rate. To exert a torque onto spacecraft, the wheel is gimbaled or rotated about a fixed axis. The rotation axis and rotation angle are referred to as the gimbal axis and gimbal angle, respectively. The advantage of CMGs is that a relatively small gimbal torque input is required to produce a large effective torque. Therefore, the CMGs produce relatively larger control torque than the RWs. For this reason, It is sometimes called torque amplifier. This makes the device popular for reorienting space structures. Consequently, the role of CMGs could be more increased than before. CMGs as well as RWs are have been applied to perform precise attitude maneuver of spacecraft instead of using thrusters,

* Research Assistant, Ph.D. Candidate
** Researcher
*** Associate Professor
E-mail : hcbang@fdcl.kaist.ac.kr TEL : 042-869-3722 FAX : 042-869-3710

since the torque could be produced continuously which is a different property from the external torquer.

In particular, the CMG cluster maximizing the torque production capability could be used as a primary actuator for the maneuverability of agile spacecraft such that the singularity problem of the CMGs emerges as one of the critical problems. At singular configurations the CMG cluster is unable to produce required torque command. When the CMG cluster is used to control agile spacecraft for various missions such as large angle re-orientation, multi-target acquisition and earth pointing, the several problems induced by the CMG cluster should be deeply considered.

Various approaches have been extensively explored to overcome the singularity problem of the CMG cluster[3]-[11]. one of the solutions is the null motion method.[7] It represents motion of the gimbals that produce no net control torque. A variety of analytic approaches to develop a proper null motion have been investigated. The gradient method to evaluate the null vector received significant attention and successfully applied to space systems. At first, a gradient vector should be computed to obtain the null vector. Effective algorithms have been developed to get the gradient vector. However, the computational burden may be still heavy.[1] In this paper, a fast algorithm to quickly compute the gradient vector is proposed by introducing a new singularity index.

To avoid singular states, usage of external devices such as thrusters has been developed. This technique turns the momentum vectors of the CMGs such that the singularity problem of the CMGs is resolved. This method can surely prevent the CMGs from entering singular configurations. However, it may not be compatible for the purpose of the precision attitude control. In this paper, the RWs are applied to overcome the singularity problem as an alternative device. Moreover, the saturation problem of the RWs is also simultaneously considered. Using the various momentum exchange devices makes the proposed hybrid control law be a feasibly approach for the purpose. Equations of motion of a rigid spacecraft consisting of multiple variable speed control moment gyros(VSCMGs) are derived. The form is transformed to various equations of motion , for example, a spacecraft with multiple CMGs and RWs. The derived form in this paper is quite affordable to design a hybrid controller using the momentum exchange devices.

The hybrid control law proposed in this paper allocates control torque to the CMGs and the RWs adequately to satisfy the precision attitude control and large angle maneuver simultaneously. The proposed law consists of several terms. each of the terms is related to the required torque command, null vector for singularity avoidance of the CMGs, and another null vector for the wheel speed regulation of the RWs, respectively. Amount of the terms can be adjusted by controlling weighting parameters. If large torque is required, for example, it is possible by relatively increasing the weighting parameters related to the RWs. The proposed hybrid control law could be effective to perform the various missions of agile spacecraft and could be of a solution to the potential problems of the momentum exchange devices.

Mathematical Model

Let a gimbal frame whose orientation is given by the unit vectors as shown in Fig. 1. Note that a is the unit gimbal axis vector, b is the spinning unit axis vector of the wheel disk and c is the unit torque axis vector. Components of the gimbal frame unit vector are assumed to be given by the spacecraft body reference frame.

Equations of motion of a rigid spacecraft with multiple VSCMGs is given by [16]

$$J\dot{\omega}+\omega^{\times}J\omega+\omega^{\times}\sum_{i=1}^{n}C_i[h_{\varpi}]_i=\sum_{i}^{n}C_i[h_t^{\times}\dot{\gamma}_g-I_t\ddot{\gamma}_g-I_g\dot{\varpi}_g]_i+u_e \tag{1}$$

Simplification of System Dynamics

There are some useless terms in Eq.(1) while making a control law using the whole equation, because certain terms make torques in negligible levels which have nearly not affected

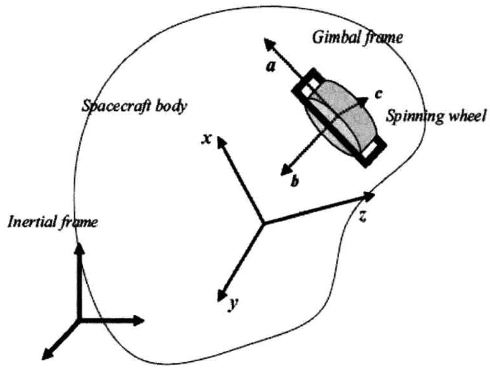

Fig. 1. Coordinate definition of spacecraft with one VSCMGs

the whole spacecraft system dynamics. One can design more substantial and practical control laws by eliminating the negligible parts of the system dynamics.

Generally, inertias of gimbal frame and wheel of CMGs are relatively very small compared with the spacecraft. The angular rate vector and acceleration vector of gimbal frame $(\dot{\gamma}, \ddot{\gamma})$ are relatively small compared with the angular rate of wheel. The angular rate of a spacecraft performing a given mission is generally small. Momentums produced by small angular rates exerted to small inertias such as the gimbal frame or the wheel could be negligible. At this point, let us make a considerably simplified system dynamics

To construct equations of motion of a spacecraft installed with several CMGs and RWs is considerable meaningful. Assume that there is a spacecraft installed with $n+m$ CMGs. The governing equation of the spacecraft with various momentum exchange devices is given by setting the angular rate of gimbals of n CMGs to zero, and fixing the angular rate of wheels of m CMGs in Eq.(1) such that $\dot{\varpi}=0$. Therefore, the system dynamics in Eq.(24) is transformed to be [16]

$$J\dot{\omega}+\omega^{\times}J\omega+\omega^{\times}(C_{wc}h_{wc}+C_{wr}h_{wr}) = -C_{\gamma c}H_{wc}\dot{\gamma}_c - C_{wr}I_{wr}\dot{\varpi}_r \qquad (2)$$

Note that subscripts c and r represent a CMG and a RW, respectively. $\dot{\gamma}_c, h_{wc} \in R^n$ are the gimbal angular rate vector and the angular momentum vector of the CMGs, respectively. $\dot{\varpi}_r, h_{wr} \in R^m$ represent the angular acceleration vector and the angular momentum vector of the RWs, respectively. $C_{wc} \in R^{3\times n}$, $C_{wr} = \in R^{3\times m}$ are matrices spanned with the unit vectors of spinning axis of CMGs and RWs, respectively,

Hybrid Controller Design

The CMGs have been suffering from singularity problem, and the RWs have the wheel saturation problem. These problems are considered simultaneously with accomplishing the purpose. A quaternion feedback law is employed for the purpose. Thus, attitude kinematics is briefly introduced, and then the nonlinear control law follows. Finally, the hybrid control law using CMGs and RWs is formulated.

Attitude Kinematics

Quaternion sometimes called Euler parameters is defined in terms of the principal rotation elements as

$$\begin{aligned} q_1 &= l_1 \sin(\Theta/2) \\ q_2 &= l_2 \sin(\Theta/2) \\ q_3 &= l_3 \sin(\Theta/2) \\ q_4 &= \cos(\Theta/2) \end{aligned} \tag{3}$$

where Θ is the principal angle, $l = [l_1, l_2, l_3]^T$ is the unit principal axis vector. There is an evident constraint given by $l_1^2 + l_2^2 + l_3^2 = 1$ which brings the following constraint

$$q_1^2 + q_2^2 + q_3^2 + q_4^2 = 1 \tag{4}$$

The kinematic differential equations for the quaternion are given by

$$\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \end{bmatrix} = \begin{bmatrix} 0 & \omega_3 & -\omega_2 & \omega_1 \\ -\omega_3 & 0 & \omega_1 & \omega_2 \\ \omega_2 & -\omega_1 & 0 & \omega_3 \\ -\omega_1 & -\omega_2 & -\omega_3 & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \tag{5}$$

By using vector notations,

$$\begin{aligned} \dot{q} &= -\frac{1}{2}\omega^{\times} q + \frac{1}{2} q_4 \omega \\ \dot{q}_4 &= \frac{-1}{2}\omega^T q \end{aligned} \tag{6}$$

Note that the vector denoted as $q = (q_1, q_2, q_3)^T$ of the quaternions is called the quaternion vector.

Quaternion Feedback Law

Generally, the gyroscopic terms are not significant for most practical attitude maneuvers of a spacecraft. However, by directly eliminating the terms, undesirable phase during the large angle maneuver can be prevented. Nonlinear quaternion feedback law is given by

$$u = kK_e e - K_\omega \omega + \omega^{\times} J\omega + \omega^{\times}(C_{wc} h_{wc} + C_{wr} h_{wr}) \tag{7}$$

where K_e and K_ω are gain matrices. Inserting the quaternion feedback law into Eq.(1) results in

$$J\dot{\omega} + K_\omega \omega + K_e e = 0 \tag{8}$$

where $e = (e_1, e_2, e_3)^T$ is an error quaternion vector. The commanded attitude quaternion vector q_c and the current attitude quaternion vector q are related to the attitude-error quaternion vector. The relationship is as follows :

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \end{bmatrix} = \begin{bmatrix} q_{4c} & q_{3c} & -q_{2c} & -q_{1c} \\ -q_{3c} & q_{4c} & q_{1c} & -q_{2c} \\ q_{2c} & -q_{1c} & q_{4c} & -q_{3c} \\ q_{1c} & q_{2c} & q_{3c} & q_{4c} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \tag{9}$$

The stability of the closed-loop system is proven by a proper selection of the gain matrices. It was shown by Wie that if the matrix $K_e^{-1} K_\omega$ is positive definite, the closed-loop system globally asymptotically stable. As one of the satisfactory conditions, $K_e = 2k_e J$ and $K_\omega = K_\omega J$ are enough, where K_e and K_ω are positive constants. For more detail gain selection methods, see Refs. 14 and 15.

Singularity Avoidance Law

The classical steering laws for CMGs are usually subject to the singularity problem when torque vectors are aligned together at the same plane or line. During last several years, various attempts have been made to solve the singularity avoidance problem. A singularity robust approach was introduced to avoid singular configurations However, this law did not always guarantee the singularity avoidance. A strategy so-called null motion was introduced with series of follow-on research works. It represents a motion of the gimbals that produce no net control torque. A variety of the analytic approaches to develop a proper null motion have been investigated. The gradient method, as one of the popular null motion approaches, received significant attention.

In this section, an optimal steering law for spacecraft with multiple CMGs in Eq.(2) as a sample system is briefly introduced. The optimization method to avoid singularity of CMGs was investigated by Lee and Bang. To avoid singular configurations for given CMGs, a cost function V, to be minimized as a measure of singularity, is selected as

$$\min_{\dot{\gamma}} v V(\dot{\gamma}) + \frac{1}{2}\dot{\gamma}^T W \dot{\gamma} \tag{10}$$

and a constraint is given by

$$A\dot{\gamma} = u \tag{11}$$

where the matrix A is defined as $-C_{\gamma} H_w$. The cost function V represents a measure of singularity which should be minimized by the gimbal angular rate. The scalar $v \in R$ and the matrix $W \in R^{n \times n}$ are the weighting parameter and matrix for the singularity cost and the energy term, respectively. The approximated optimal solution for the given cost and the constraint is given by [13]

$$\begin{aligned} \dot{\gamma} &= H^{-1}A^T(AH^{-1}A^T)^{-1}u \\ &+ [H^{-1}A^T(AH^{-1}A^T)^{-1}AH^{-1} - H^{-1}]g \end{aligned} \tag{12}$$

where the updated Hessian is defined as $H = \overline{H} + W$. The Hessian $\overline{H}$ and the gradient vector g are defined by partial derivatives of a given singularity cost as

$$\overline{H} = \Delta t \frac{\partial^2 V}{\partial \gamma^2}, \quad g = \frac{\partial V}{\partial \gamma} \tag{13}$$

where Δt is time interval, If Δt can be assumed to be zero such that the Hessian could be zero matrix. Substitution of $\overline{H} = 0$ into Eq.(12) results that the optimal steering law could be identical with conventional null motion methods. As a cost function to measure singular conditions, the condition number of A or the non-dimensional condition number defined as

$$V = \frac{\sigma_1}{\sigma_3} \tag{14}$$

has been widely used. In the above equation σ_i are the singular values of A. It is assumed that they have been arranged such that $\sigma_1 \geq \sigma_2 \geq \sigma_3$. To reduce computational burden Schaub and Junkins provided an useful algorithm to quickly compute $\partial V / \partial \gamma$. Even though they provided the quick algorithm, the computational burden of SVD may be still heavy.[1]

An alternative to the singularity index is introduced to quickly calculate the null vector of A for avoiding singular configurations. Assume that all the inner products of two different column vectors of a given matrix are all zeros such that the column vectors are orthogonal one another's vectors. This means that the matrix has full rank and a non-singular configuration. Therefore, the inner product related cost can be a singularity measure such that the index is defined as

$$V = \frac{1}{2} \sum_{i,j=1, i \neq j}^{n} \langle c_i, c_j \rangle^2 \tag{15}$$

A useful property is formulated such that the derivatives of the unit vectors with respect to gimbal rates are given by

$$\frac{\partial b_i}{\partial \gamma_i} = c_i, \quad \frac{\partial c_i}{\partial \gamma_i} = -b_i \tag{16}$$

and

$$\frac{\partial^2 b_i}{\partial \gamma_i^2} = -b_i \tag{17}$$

By applying the property in Eq.(13), the i-th element of the gradient vector is compactly found to be

$$g_i = \sum_{i,j=1, i \neq j}^{n} \langle c_i, c_j \rangle \langle b_i, c_j \rangle \tag{18}$$

If the optimal steering law is applied to a continuously controlled system such that only the gradient vector is required, the computational burden to construct optimal gimbal rates for singularity avoidance could be effectively reduced. Even though the Hessian is required to avoid singular configurations for a given CMG, it can be readily obtained by applying the properties in Eqs.(16) and (17). The element of the Hessian is of the form:

$$\frac{\partial^2 V}{\partial \gamma_i^2} = \sum_{\substack{i,j=1 \\ i \neq j}}^{n} \langle b_i, c_j \rangle^2 - \langle c_i, c_j \rangle^2 \tag{19}$$

$$\frac{\partial^2 V}{\partial \gamma_i \gamma_j} = \langle b_i, c_j \rangle \langle c_i, b_j \rangle + \langle c_i, c_j \rangle \langle b_i, b_j \rangle$$

Only the spinning vector b_i and torque unit vector c_i are used to evaluate the Hessian.

Hybrid Control Using CMGs and RWs

The momentum exchange devices are chosen as CMGs and RWs to formulate a hybrid controller. The purpose raised in this paper should be achieved simultaneously by resolving the singular problem of CMGs and the saturation problem of RWs. Therefore, it is important to take advantages of each device. Proper combination of the merits can be a solution of the problems. As one of the potential approaches, optimization theory can be a proper method to satisfy the purpose.

To apply optimization theory, it is important to search a cost function to avoid singular configurations of CMGs and not to excess wheel speed of RWs for a given speed limit. Therefore, a constrained optimization problem can be formulated by defining a cost function as

$$\min_{\dot{\gamma}, \dot{\varpi}} \left[v V + \frac{1}{2}(\dot{\varpi} - \dot{\varpi}_d)^T Z (\dot{\varpi} - \dot{\varpi}_d) + \frac{1}{2}\dot{\gamma}^T W \dot{\gamma} + \frac{1}{2}\dot{\varpi}^T Y \dot{\varpi} \right] \tag{20}$$

with the torque command constraint given in

$$A\dot{\gamma} + B\dot{\varpi} = u \tag{21}$$

where the matrices A and B are defined as

$$A = -C_{\gamma c} H_{wc}, \qquad B = -C_{wr} I_{wr} \tag{22}$$

Subscripts r and w can be dropped in $\dot{\gamma}$ and $\dot{\varpi}$ without confusion in this case for the sake of convenience. $\dot{\varpi} \in R^m$ is a wheel angular acceleration vector of reaction wheels. Y and $Z \in R^{m \times m}$ are the weighting matrices, and $\dot{\varpi}_d$ represents the preferred wheel speed vector defined as

$$\dot{\varpi}_d = \frac{\varpi_d - \varpi}{\Delta t} \tag{23}$$

The singularity cost function and the weighting parameter are equivalently used with the optimal steering law described in the previous section. The first two terms of the given cost function are defined to minimize the singular index of CMGs and regulate the wheel speed of RWs, respectively. The last two terms are related to the energy of CMGs and RWs, respectively. To obtain a closed-form solution for the hybrid control, optimality conditions are used such that the state vectors are of the form :

$$\begin{aligned} \dot{\gamma} &= -H^{-1}(A^T\lambda+g) \\ \varpi &= -X^{-1}(B^T\lambda+p) \end{aligned} \tag{24}$$

for consistency, the new notations are defined as

$$\begin{aligned} X &= Y+Z \\ p &= -Z\dot{\varpi}_d \end{aligned} \tag{25}$$

The vector p can be interpreted as a gradient vector for wheel speed regulations, and $\lambda \in R^3$ is a Lagrange multiplier vector. By replacing the two state vectors into Eq.(21), the Lagrange vector can be easily found to be

$$\lambda = -C^+u - C^+AH^{-1}g - C^+BX^{-1}p \tag{26}$$

for simplification, the matrix is defined as

$$C^+ = (AH^{-1}A^T + BX^{-1}B^T)^{-1} \tag{27}$$

Inserting the Lagrange multiplier vector into the optimality conditions results in

$$\begin{aligned} \dot{\gamma} &= PC^+u + (PC^+P^T - H^{-1})g + PC^+Q^Tp \\ \dot{\varpi} &= QC^+u + (QC^+Q^T - X^{-1})p + QC^+P^Tg \end{aligned} \tag{28}$$

where

$$P = H^{-1}A^T, \quad Q = X^{-1}B^T \tag{29}$$

Finally, the proposed closed-loop hybrid control for large angle attitude control by using CMGs and RWs is constructed. The precision attitude control may be achieved by adjusting the weighing matrices. If a large torque is required, portion of the CMGs should be increased. This strategy can be possible by decreasing the weighting matrix W or increasing Y. If precision control phase is important, portion of the RWs should be increased. Consequently, by properly adjusting the weighting matrices as a function of a given control torque command the purpose could be achieved satisfactorily.

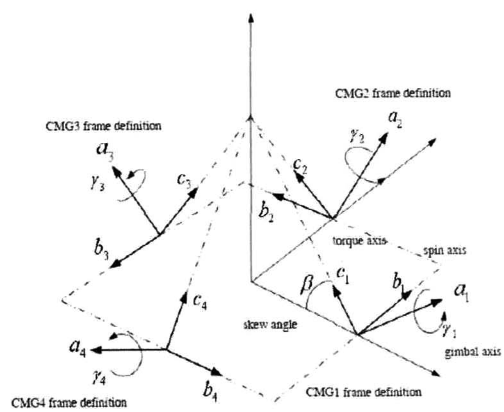

Fig. 2. Pyramid Type CMG configuration

Simulation Study

In this section, various simulations are performed to demonstrate the proposed hybrid control law in Eq.(54). The target model is the spacecraft installed with pyramid-type CMG and RW cluster illustrated in Fig. 2. That is, four CMGs and four RWs are used. Numerical simulation parameters are listed in Table. 1. The skew angles of β_c and β_r are for the CMG and RW configuration, respectively. The angles have been generally studied and applied to the space systems. Wheels of the CMGs are assumed to be initially rotating about 2000rpm to generate momentum vectors. The desired quaternion is arbitrary selected and the profile of the attitude is illustrated in Fig. 3. The required torque command to satisfy the desired attitude command based on the quaternion feedback gains of k_ω and k_e is shown in Fig. 4.

Table 1. Numerical simulation parameters

Symbol	Value
Δt	0.01 sec
J	diag[2500, 1000, 2000] kg m^2
I_d	diag[1.0, 3.2, 1.0] kg m^2
I_w	diag[1.0, 4.0, 1.0] kg m^2
ϖ_c	2000 rpm
ϖ_d	$[0, 0, 0]^T$ rad/s
k_e	16.0
k_w	2.8
β_c	36.0°
β_r	45.0°
$q(0), q_4(0)$	$[-0.6922, -0.0691, 0.6887, 0.2045]^T$

Table 2. Weighting parameters

Symbol	Nominal	Only RW	Without null	With null	Hybrid
W	$W_n = I_{4\times4}$	×	$I_{4\times4}$	$0.1W_n$	$0.1W_n$
Y	$Y_n = 5\times10^{-6}I_{4\times4}$	$I_{4\times4}$	×	×	$10.0Y_n$
Z	$Z_n = Y_n$	×	×	×	Z_n

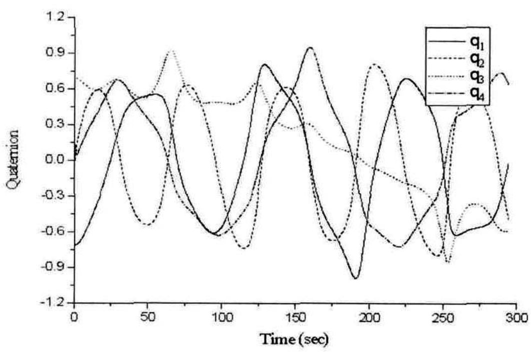

Fig. 3. Desired spacecraft attitude

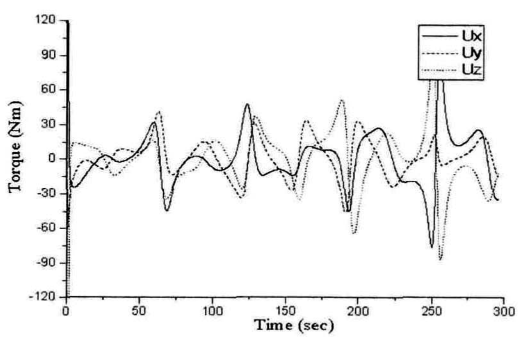

Fig. 4. Required control torque

Several weighting matrices to design a generic RW controller, CMG controller and a hybrid control logic are listed in Table. 2. The nominal case means that the portion of the control torque is fairly divided such that the CMG cluster and four RWs produce 50% control torque, respectively. At first, the spacecraft is controlled by only four RWs. To produce fully enough control torque to reorient the spacecraft, the profiles of the angular acceleration and rate of the RWs are shown in Fig. 5. Large angular acceleration at 250 seconds is required such that it

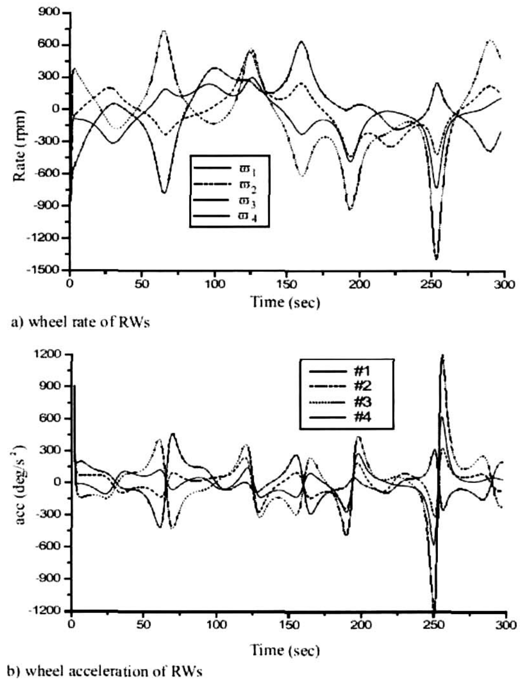

Fig. 5. Response of only 4 RWs

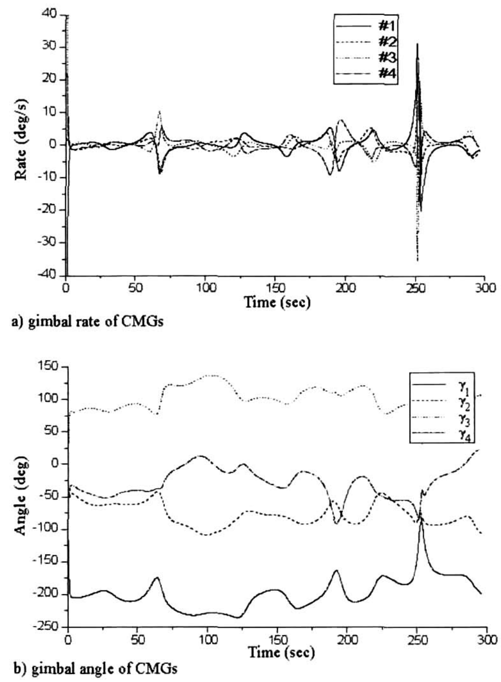

Fig. 6. Response of CMGs without null motion

introduces large wheel rate at that time. This large acceleration and rate of the wheels can be a critical problem ,namely, saturation when the RWs are used as primary actuators.

The pyramid-type CMG cluster is only used for the next two simulations to demonstrate the avoidance level of the singularity between the general pseud-inverse method and the optimal steering law with the proposed fast gradient method in this paper. The response of CMGs without the null motion strategy is shown in Fig. 6. It is also required high angular rate of the wheel at 250 second. One can see that a bad condition number of A illustrated in Fig. 8 introduces the undesirable result. In the high condition number, some torque vectors could require unrealistic high gimbal rates. That is, it is important to keep the condition number in a low level. The results in Fig. 7 is the response induced by the optimal steering law. The overall aspects of the gimbal rate and angle of the CMGs are in a reasonable level. The effective gradient vector in Eq.(44) and Hessian in Eq.(45) proposed in this paper is successfully applied to avoid the singularity. The dramatically reduced condition number of the null motion strategy illustrated in Fig. 8 guarantees the performance of the optimal steering law. However, if more large torque is required to control the agile spacecraft, the condition number of the CMG cluster having limited gimbal rates could be increased.

The four RWs are added to keep the condition number in a consistent low level. The proposed hybrid strategy can be applicable by properly allocating the control torque to the RWs. That is, it is possible by adequately adjusting the weighting parameters. One of weighting choices for the hybrid is placed in Table. 2. The response of the condition number is also plotted in Fig.8. The effectiveness can be proven from the result that the condition number is uniformly regulated in a low level by the help of the RWs.

Next simulation results shown in Figs 9 are for the nominal case. The gimbal rate and the wheel acceleration are properly divided such that the overall responses take on smooth aspects. Moreover, from the condition number in Fig. 10 one can inference the performance of the hybrid control law to be enhanced. The proposed law can show up with various appearance by the variation of the weighting matrices. To decrease the rate of the RWs the weighting matrix of Y should be increased. On the lip side, the weighting matrices of W, Y should be decreased to avoid

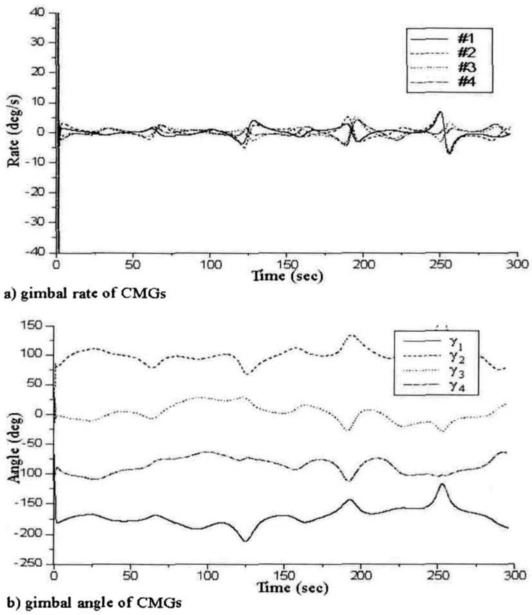

Fig. 7. Response of CMGs with null motion

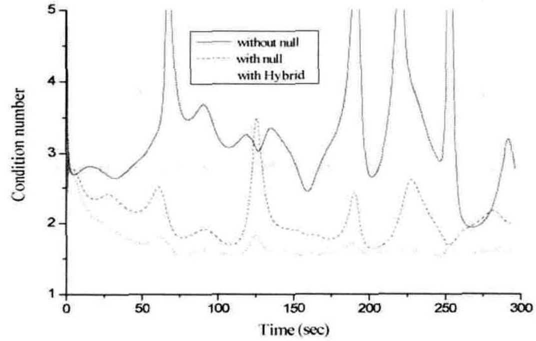

Fig. 8. Comparison of the condition numbers

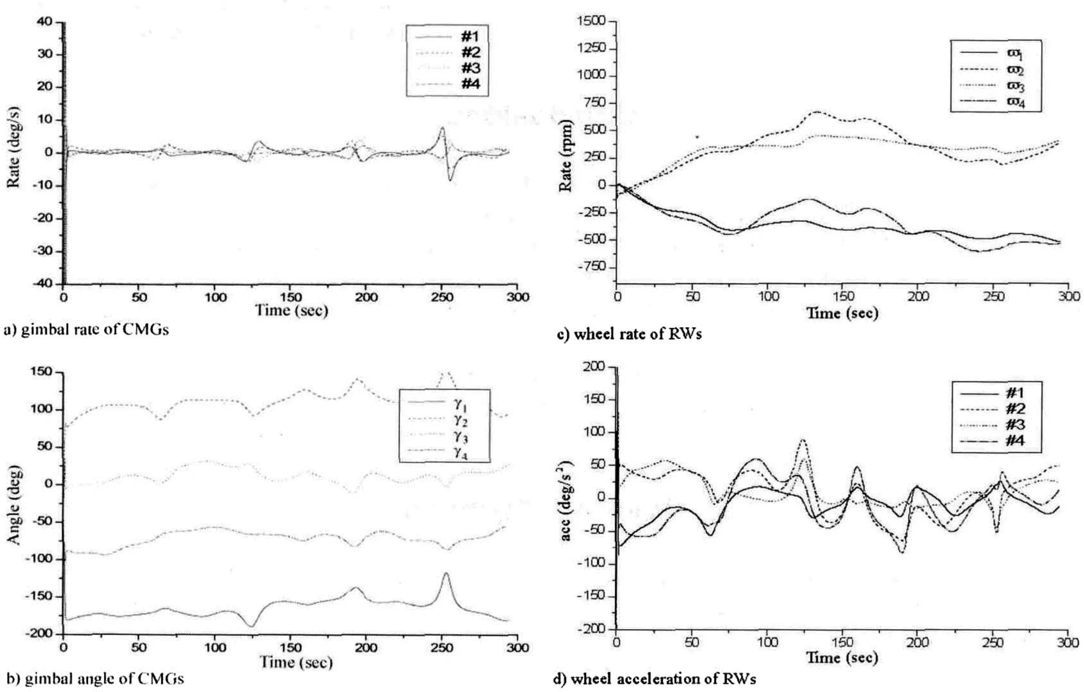

Fig. 9. Gimbal of CMGs in the nominal case

the singularity or to decrease the condition number. The aspects by the variation of the weighting matrices are illustrated well in Fig. 11. As Y is increased, the condition numbers are being increased. On the other hand, the maximum speed of the RWs is being decreased. Thus, one should properly select the weighting matrices considering the specification of CMGs and RWs for the precision attitude control of agile spacecraft.

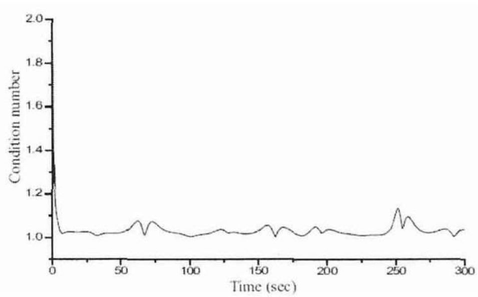

Fig. 10. condition number in the nominal

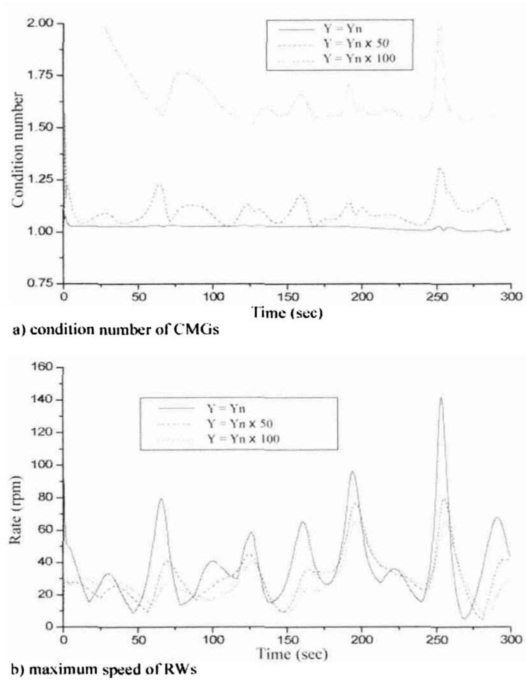

Fig. 11. Comparison in accordance with weighting matrix variations

Conclusions

In this paper, a hybrid control law using various momentum exchange devices for precision attitude control of agile spacecraft was proposed. A nicely arranged model of spacecraft installed several CMGs and RWs was formulated. To obtain the gradient vector to generate null vector for the singularity avoidance, an effective cost function was proposed and the performance was demonstrated from simulation studies. Singularity avoidance with help of RWs was resolved, and the saturation problem of RWs was also potentially resolved by adjusting the weighting matrices. It was turn out that the precision attitude control of agile spacecraft could be performed by the proposed law using only the momentum exchange devices. Consequently, the hybrid control law proposed in this paper is applicable to the next generation high performance spacecraft.

Acknowledgement

The present study was supported by National Research Lab.(NRL) Program(2002, M1-0203-00-0006) by the Ministry of Science and Technology, Korea. Authors fully appreciate the financial support.

References

1. Junkins, J. L., and Kim. Y., *Introduction to Dynamics and Control of Flexible Structures* AIAA, Washington, DC, 1993, pp. 9-64.

2. Nakamura, Y., and Hanafusa, H., "Inverse Kinematic Solutions with Singularity Robustness for Robot Manipulator Control", *Journal of Dynamic Systems, Measurement, and Control*, Vol. 108, Sept. 1986, pp. 163-171.

3. Wie. B., Bailey. D., and Heiberg. C., "Singularity Robust Steering Logic for Redundant Single-Gimbal Control Moment Gyros", *Journal of Guidance, Control, and Dynamics*, Vol. 24, No. 5, 2001, pp. 865-872.

4. Oh, H., and Vadali, S. R., "Feedback Control and Steering Laws for Spacecraft Using Single Gimbal Control Moment Gyros", *The Journal of the Astronautical Sciences*, Vol. 39, No. 2, 1994, pp. 183-203.

5. Wie. B., "Singularity Analysis and Visualization for Single-Gimbal Control Moment Gyro Systems", *Journal of Guidance, Control, and Dynamics*, Vol. 27, No. 2, 2004, pp. 271-282.

6. Bedrossian, N. S., Paradiso, J., Bergmann, E. V., and Rowell, D., "Steering Law Design for Redundant Single-Gimbal Control Moment Gyroscopes", *Journal of Guidance, Control, and Dynamics*, Vol.13, No.6, 1990, pp. 1083-1089.

7. Schaub, H., and Junkins, J. L., "Singularity Avoidance Using Null Motion and Variable-Speed Control Moment Gyros", *Journal of Guidance, Control, and Dynamics*, Vol. 23, No. 1, 2000, pp. 1-16.

8. Yoon, H., and Tsiotras. P., "Singularity Analysis of Variable-Speed Control Moment Gyros", *Journal of Guidance, Control, and Dynamics*, Vol. 27, No. 3, 2004, pp. 374-386.

9. Ford, K. A., and Hall, C. D., ''Flexible Spacecraft Reorientations Using Gimbaled Momentum Wheels", *Advances in the Astronautical Sciences, Astrodynamics*, Vol. 97, San Diego, CA, 1997, pp. 1895-1914.

10. Schaub, H., and Vadali, S. R., and Junkins, J. L., "Feedback Control Law for Variable Speed Control Moment Gyrocopes", *Journal of the Astronautical Sciences*, Vol. 46, No. 3, 1998, pp. 307-328.

11. Yoon, H., and Tsiotras. P., "Spacecraft Adaptive Attitude and Power Tracking with Variable Speed Control Moment Gyroscopes", *Journal of Guidance, Control, and Dynamics*, Vol. 25, No. 6, 2002, pp. 1081-1090.

12. Bryson, A. E., Jr., and Ho, Y.-C., *Applied Optimal Control, Hemisphere*, Washington, DC, 1975.

13. Lee, H., and Bang, H., "Optimal Steering Laws for Variable Speed Control Moment Gyros", *AIAA GN\&C Conference*, San Francisco, Aug, 2005.

14. Wie, B., and Barba., P. M., "Quaternion Feedback for Spacecraft Large Angle Maneuvers", *Journal of Guidance, Control, and Dynamics*, Vol. 3, No. 3, 1985, pp. 360-365.

15. Wie, B., Weiss, H., and Arapostathis, A., "Quaternion Feedback Regulator for Spacecraft Eigen-axis Rotations", *Journal of Guidance, Control, and Dynamics*, Vol. 12, No. 3, 1989, pp. 375-380.

16. Lee, H., Lee, D., and Bang, H., "Hybrid Control of Spacecraft Using Various Momentum Exchange Devices", *The 5th Asian Control Conference*, Bali, Indonesia, July, 2006.