# Magnetic Support System for a Dual-Spin Space Station

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## ABSTRACT

For space environment operations, it is desirable to have some artificial gravity to prevent physiological damage to crew members during a long stay in a zero gravity condition in outer space. Therefore, some gravity is indispensable to maintain crew's health and their task execution capability. From the space utilization viewpoint, on the contrary, microgravity environments should be provided to enable scientists and engineers to carry out their proposed experiments.

To realize the above mentioned capabilities, a dual-spin space station, supported by magnetic bearings, which provides artificial gravity and microgravity simultaneously in separate sections, was proposed. The magnetic support system is the main structure of this station, which separates both sections mechanically for vibration isolation and also acts as the main actuator to control the coning motion produced by the gyro effects from the rotating section.

This paper shows the design concept for this space station, the formulation of this dynamic model and the results of the parametric evaluations on the magnetic support system.

## INTRODUCTION

An artificial gravity space station with microgravity environments is an attractive and feasible space infrastructure in the near future. For a long stay in space, it is desirable to have some artificial gravity to prevent physiological damage to the crew members during a long stay in the zero gravity condition in outer space. Therefore, some gravity is indispensable to maintain crew's health and their task execution capability. From the space utilization viewpoint, on the contrary, microgravity environments should be provided to enable scientists and engineers to carry out their proposed experiments.

Several studies have been conducted regarding space stations with an artificial gravity and their related technologies [1-3]. Wenglarz [4,5] has analyzed a dynamic model for artificial "G" stations, which will provide artificial gravity and zero gravity environments simultaneously in separate sections, with rigid or low-coupling interconnections. Nitta [6] and Nakajima [7] have proposed a dual-spin space station with both environments. This space station is composed of a non-rotating microgravity section at the center, a rotating artificial gravity section and a transit cabin used for transportation between them. The rotating section generates the artificial gravity, whose value depends on the rotating speed and radius. 1 [g] is generated by

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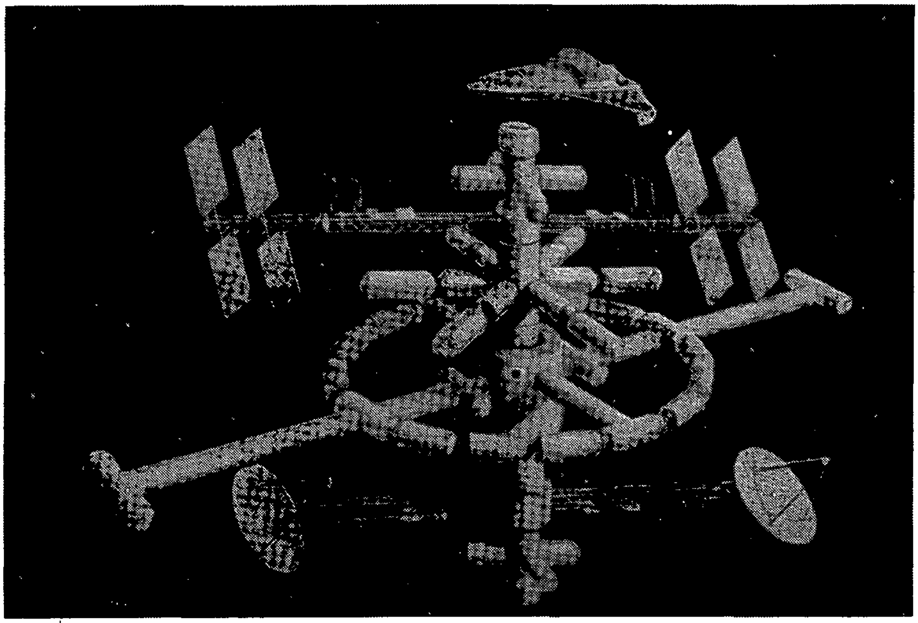

Figure 1. Dual-Spin Space Station Configuration

3 rpm rotating speed with 100-meter radius. The non rotating, despun section maintains the microgravity environment. The magnetic support system is the main structure in this station, which separates the sections mechanically for vibration isolation. It also acts as the main actuator to control the coning motion produced by gyro effects from the rotating section. The transit cabin is designed to transport the crew and instruments from one section to the other without EVA (Extra Vehicular Activity). Figure 1 shows the configuration for this proposed space station with an artificial gravity.

This paper reports the design concept for this space station, the formulation of this dynamic model and parametric evaluations on the magnetic support system.

## SPACE STATION MODEL [8-10]

The dynamic model for the dual-spin space station, supported with magnetic bearings, and its coordinate system are shown in Fig.2. It consists of two sections, a rotating artificial gravity section and a despun zero gravity section, both of which are connected with magnetic bearings without any mechanical contact.

System details and terminology are given as follows: The rotating section is termed body R and the other section is termed body S. The rotor is an axisymmetric rigid body with mass $m_R$, whose center of mass $C_R$. A

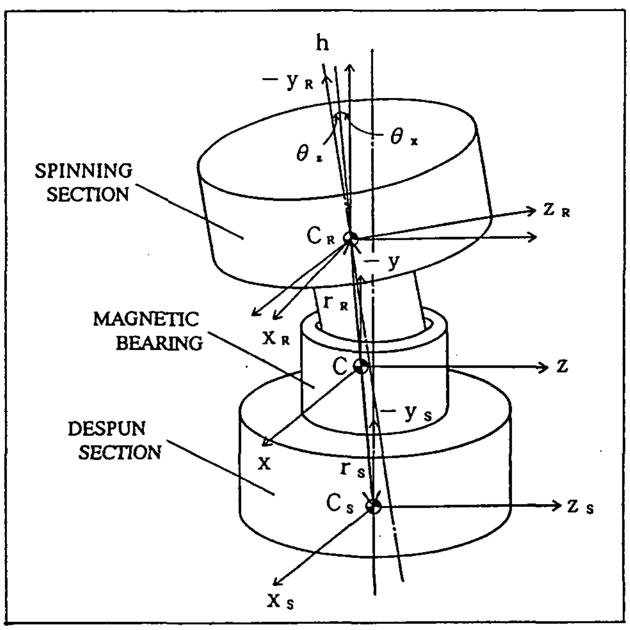


Figure 2. Model and its Coordinate System

body fixed to the rotor coordinate system is defined by the triad $(x_R, y_R, z_R)$ with its origin at the rotor center of mass. The stator is an axisymmetric rigid body with mass $m_S$, whose center of mass is $C_S$. A body fixed stator coordinate system is defined by the triad $(x_S, y_S, z_S)$ with its origin at the stator center of mass. A third coordinate system is defined by the triad (x, y, z) at the system's center of mass C, whose axis is parallel to the stator coordinate system at all times. $\bar{r}_R$ is a vector from the system center of mass to the rotor and $r_S$ is a vector from the system center of mass to the stator. Rotations $\theta_x$ about the x axis and $\theta_z$ about the z axis describe the relative angles (in other words; gimbal angles) between the two bodies, which are observed by the position sensors attached on the stator. The nutational motion of the system will be attenuated by feeding back these signals to the controllers for the magnetic bearings.

## EQUATIONS OF MOTION

The inertia matrix for the rotor in the R coordinate is given in the form:

$$I_R = \begin{bmatrix} I_{RT} & 0 & 0 \\ 0 & I_{Ry} & 0 \\ 0 & 0 & I_{RT} \end{bmatrix} \tag{1}$$

The inertia matrix for the stator is also given as

$$I_S = \begin{bmatrix} I_{Sx} & 0 & 0 \\ 0 & I_{Sy} & 0 \\ 0 & 0 & I_{Sz} \end{bmatrix} \tag{2}$$

The angular velocities for the rotor, relative to the inertially fixed axis, are approximately given as follows:

$$\begin{bmatrix} \omega_{Rx} \\ \omega_{Ry} \\ \omega_{Rz} \end{bmatrix} \approx \begin{bmatrix} \dot{\theta}_x + h\theta_z/I_{Ry} + \omega_{Sx} \\ -h/I_{Ry} + \omega_{Sy} \\ \dot{\theta}_z - h\theta_x/I_{Ry} + \omega_{Sz} \end{bmatrix} \tag{3}$$

where $\theta_x$ and $\theta_z$ are sufficiently small and the products of $\theta$ are neglected.

The total angular momentum vector for the system $\bar{H}$ is expressed as follows:

$$\bar{H} = \bar{H}_R + \bar{H}_S$$

$$= m_R \bar{r}_R \times \bar{v}_R + I_R' \bar{\omega}_R + m_S \bar{r}_S \times \bar{v}_S + I_S \bar{\omega}_S$$

$$= m\bar{r} \times \bar{\omega}_S \times \bar{r} + I_R' \bar{\omega}_R + I_S \bar{\omega}_S$$

$$\approx \begin{bmatrix} (my_0^2+I_{RT}+I_{Sx})\omega_{Sx}+I_{RT}\dot{\theta}_x+h\theta_z \\ (I_{Ry}+I_{Sy})\omega_{Sy}-h \\ (my_0^2+I_{RT}+I_{Sz})\omega_{Sz}+I_{RT}\dot{\theta}_z-h\theta_x \end{bmatrix} \tag{4}$$

where

$$\bar{r} = \bar{r}_R-\bar{r}_S \tag{5}$$

$$m_R\bar{r}_R + m_S\bar{r}_S=0 \tag{6}$$

$$m = \frac{m_R m_S}{m_R+m_S} \tag{7}$$

$$I_R' \approx \begin{bmatrix} I_{RT} & (I_{RT}-I_{Ry})\theta_z & 0 \\ (I_{RT}-I_{Ry})\theta_z & I_{Ry} & (I_{Ry}-I_{RT})\theta_x \\ 0 & (I_{Ry}-I_{RT})\theta_x & I_{RT} \end{bmatrix} \tag{8}$$

$\bar{v}_i$ and $\bar{\omega}_i$ represent the linear and angular velocities for the body i (i=R,S), respectively, $y_0$ is the distance from the rotor center of mass to the stator center of mass and m is the reduced mass. $I_R'$ is the transformation matrix for $I_R$.

The time derivative for Eq.(4) in the inertial frame is

$$\left.\frac{d\bar{H}}{dt}\right|_{space} = \left.\frac{d\bar{H}}{dt}\right|_{body} +\bar{\omega} \times \bar{H} = \sum \bar{T} \tag{9}$$

where T denotes the external torque. From Eqs. (4) and (9), the linearized equations of motion for the system are expressed as follows:

$$(my_0^2+I_{RT}+I_{Sx})\dot{\omega}_{Sx}+I_{RT}\ddot{\theta}_x+h(\dot{\theta}_z+\omega_{Sz}) = T_x \tag{10}$$

$$(I_{Ry}+I_{Sy})\dot{\omega}_{Sy}-\dot{h} = T_y \tag{11}$$

$$(my_0^2+I_{RT}+I_{Sz})\dot{\omega}_{Sz}+I_{RT}\ddot{\theta}_z-h(\dot{\theta}_x+\omega_{Sx}) = T_z \tag{12}$$

By applying the same procedure to the rotor system, the linearized equations of motion are expressed as follows:

$$(m_R y_R^2+I_{RT})(\ddot{\theta}_x+\dot{\omega}_{Sx})+h\left\{\left(1+\frac{m_R y_R^2}{I_{Ry}}\right)\dot{\theta}_z+\omega_{Sz}\right\} =T_{cx} \tag{13}$$

$$I_{Ry}\dot{\omega}_{Sy}-\dot{h} = T_{cy} \tag{14}$$

$$(m_R y_R^2+I_{RT})(\ddot{\theta}_z+\dot{\omega}_{Sz})-h\left\{\left(1+\frac{m_R y_R^2}{I_{Ry}}\right)\dot{\theta}_x+\omega_{Sx}\right\} =T_{cz} \tag{15}$$

where $T_c$ ( $T_{cx}$, $T_{cy}$ and $T_{cz}$ ) is a supplemental control torque which is mainly produced by the magnetic support system.

Equations (11) and (14) represent the dynamics about the spin axis, while Eqs. (10), (12), (13) and (15) represent the oscillatory motions for the system. Their frequencies and damping characteristics are focused on in the discussion presented in this paper.

## NUMERICAL EXAMPLES

Three oscillatory roots exist in this system, derived from the four linearized equations (10), (12), (13) and (15). They are the eigenvalues for the rotor, gimbal and stator, respectively.

The transfer function for the magnetic bearings' controller is assumed to follow the formula

$$\frac{T_c(s)}{\theta(s)} = -\left[\frac{1}{1+\tau_I s} \cdot G\,\frac{1+\tau_1 s}{1+\tau_2 s}\right]\theta_x \tag{16}$$

where G is the linear gain and is equivalent to the stiffness of the magnetic bearings, $\tau_1$ and $\tau_2$ are the time constants for the lead/lag compensator and $\tau_I$ is the time constant for the power amplifier. The control torques, represented in the right hand terms in Eqs.(13) and (15) are replaced by $T_c$, defined as Eq.(16).

Figure 3 shows the root loci for the variable G system. Two roots, near the origin, represent the nutational motion for the stator and related gimbal oscillation with long periods. Another two roots represent the oscillations related to the rotor and lead/lag compensator. According to G increase, nutational mode approaches the imaginary axis. On the contrary, the other modes remain stable and have sufficient damping characteristics.

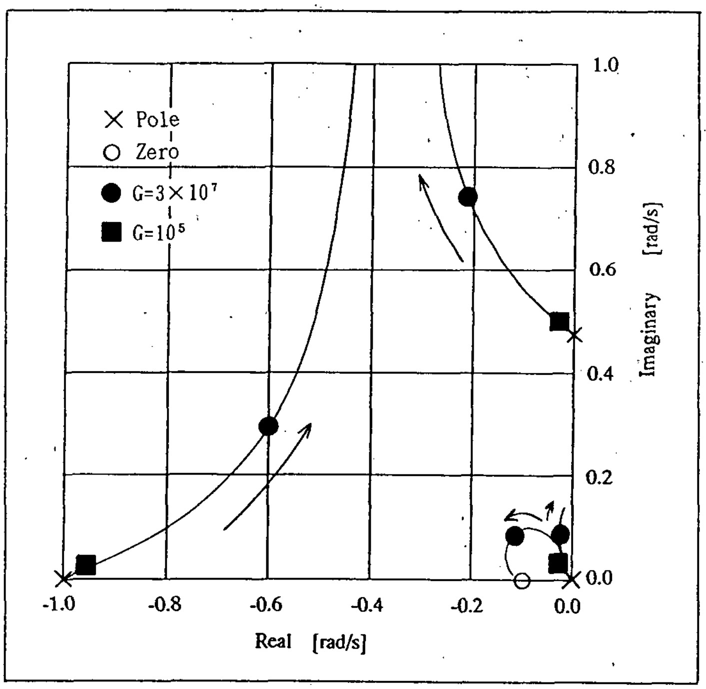


Figure 3 Root Loci for the Variable G System

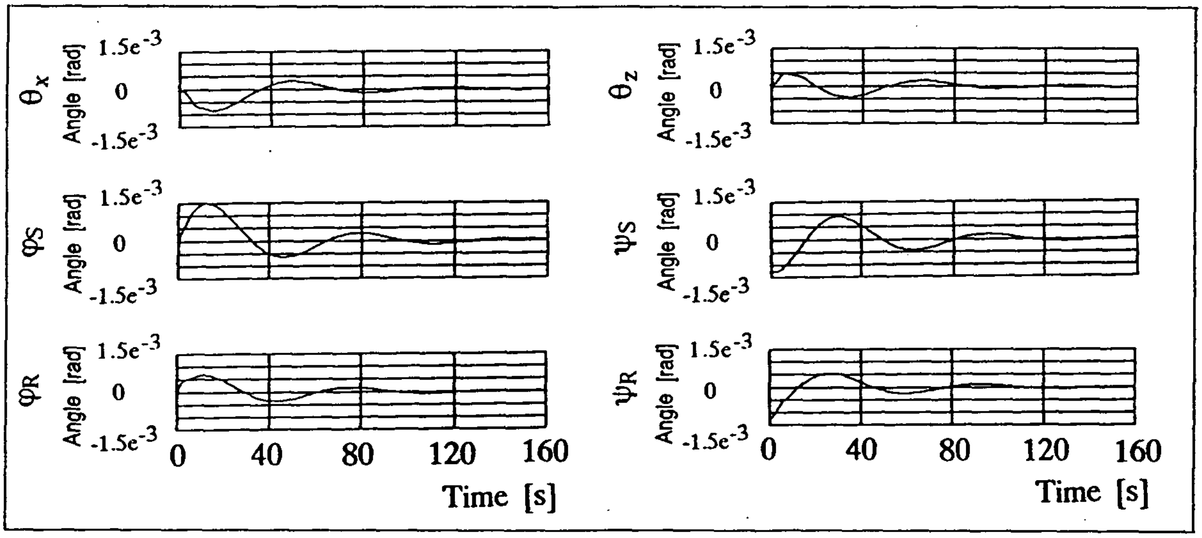


Figure 4 Computer Simulation Results

Figure 4 shows computer simulation results, when the G value is $3 \times 10^7$ [Nm/rad], as an example case. The nutation period becomes 64.8[s]. The differential equations are numerically integrated by the RKG method, with every 0.1 second time interval. $\varphi$ and $\psi$ represent euler angles, whose initial values are given as $\varphi_S=\varphi_R=0$[rad], $\psi_S=\psi_R=-0.0013$[rad] and the initial values of the gimbal angles, $\theta_x$ and $\theta_z$, are also zero. The total angular momentum vector coincides with -Y axis. Figure 4 shows that the controller has sufficient damping characteristics and that all oscillatory motions decrease within a few minutes (Damping ratio $\zeta$ is about 0.2).

System parameters are listed in Table I. Both centers of mass coincide with the center of the total system. Each section has an axisymmetric body. The angular momentum for the rotor is given as $4.71 \times 10^8$ [Nms], which is calculated for 1 [g] artificial gravity generation at 100 [meter] radius point with 3 [rpm] rotation. Time constant $\tau$ is chosen, as an example, mainly to compensate for the low frequency range.

Table I - SYSTEM PARAMETERS

| Item | Value | | Item | Value | |
|---|---|---|---|---|---|
| $I_{Sx}$ | $2 \times 10^9$ | [$kgm^2$] | $y_0$ | 0 | [meter] |
| $I_{Sy}$ | $10^9$ | [$kgm^2$] | $y_S$ | 0 | [meter] |
| $I_{Sz}$ | $2 \times 10^9$ | [$kgm^2$] | $y_R$ | 0 | [meter] |
| $I_{RT}$ | $1 \times 10^9$ | [$kgm^2$] | h | $4.71 \times 10^8$ | [Nms] |
| $I_{Ry}$ | $1.5 \times 10^9$ | [$kgm^2$] | $\tau_1$ | 10 | [s] |
| $m_S$ | $1.2 \times 10^5$ | [kg] | $\tau_2$ | 1 | [s] |
| $m_R$ | $2 \times 10^5$ | [kg] | $\tau_I$ | 0.1 | [s] |
| m | $7.5 \times 10^4$ | [kg] | G | variable | [Nm/rad] |

## MAGNETIC SUPPORT SYSTEM

The previous section has clarified that the system has sufficient damping characteristics, if the control gain could be obtained as desired values. Under a certain restriction, on the contrary, the system would not have sufficient damping effect. As a concrete example, the controller gain for the magnetic bearings is given at about 1/100 of that for the above simulated case. At this time, the roots mostly remain at the starting points in Fig.3. The damping ratios are about 0.03 for the nutational mode and about 0.001 for the rotor, when system gain $G=10^5$.

The system gain mainly depends on the hardware configuration for the magnetic support system and its control electronics. The estimated specifications for the magnetic support system are given in Table II. Because of the large gaps between rotor and stator, the coil ampere turns are too large to obtain a sufficient gap flux density, using ordinary electro-magnets. The super conducting coil would be a possible candidate to solve this problem.

Table II - MAGNETIC SUPPORT SYSTEM

| Items | Estimated Specifications | |
|---|---|---|
| Number of Magnets (Radial/Conical/Axial) | 10 or more | |
| Diameter | 6.0 | [meter] |
| Length (Distance between upper and lower Magnet centers) | 6.0 | [meter] |
| Gap (Distance between Rotor and Stator) | 0.15 | [meter] |
| Gap Flux Density | 0.01 | [T] |
| Ampere Turns | about $10^7$ | [AT] |
| Magnetic Force | about $10^3$ | [N] |
| Magnetic Torque | about $10^4$ | [Nm] |
| Possible System Gain | about $10^7$ max | [Nm/rad] |

## CONCLUSION

The dynamic model for the proposed dual-spin space station and its linearized equations of motion are derived. The three oscillatory motions are attenuated by appropriately controlling the magnetic support system. The damping characteristics fully depend on the system gain, in other words, the stiffness of the magnetic bearings. Because of the large gaps between the rotating section and the despun section, it is not easy to assure sufficient magnetic flux density to produce the effective control torques, using only ordinary electro-magnets. Super conducting coils or other auxiliary actuators would be necessary to control the gyroscopic motion directly with the large dynamic range indicated in this paper. An actual case, on the contrary, disturbance torques acting on a space station in orbit are small, so that the attitude motion could be compensated for by activiating the magnetic support system proposed in this paper.

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