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CONTROL OF SPACE STATIONS

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ABSTRACT

A study is made to develop controllers for the NASA-JSC Triangular Space Station and evaluate their performances to make recommendations for structural design and/or control alternatives. The control system design assumes the rigid body of the Space Station and developes the lumped parameter control system by using the Inverse Optimal Control Theory. In order to evaluate the performance of the control system, a Parameter Estimation algorithm is being developed which will be used in modeling an equivalent but simpler Space Station model. Finally, a scaled version of the Space Station is being built for the purpose of physical experiments to evaluate the control system performance.

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INTRODUCTION

For the case of advanced spacecraft such as the proposed Space Station, attitude control has typically been a major problem. The source of previous control difficulty has been centered on the requirement to control a highly flexible vehicle. Spacecrafts with cantilevered solar panels cause particular problems because of the low frequencies of the flex modes. If a classical control strategy is used, the flex modes are filtered out of the sensed vehicle response. This technique, unfortunately, has an adverse effect on the attitude control performance of the vehicle. In addition, the closed loop stability of the flex modes is not guaranteed for highly flexible appendages. For highly flexible structures the control system must not only account for attitude control, but also must exhibit vibration control features.

The Preliminary Space Station Design Team of the Structures Division of NASA-JSC has developed an alternative triangular configuration [Schneider,1982] for future Space Station in order to minimize the attitude control problem which is inherent in many proposed Space Station configurations. The flex mode of this configuration are relatively high (>5.4 Hz) and therefore can be filtered out of the sensed vehicle response. This allows rigid body control below the flex frequency bandwidth with acceptable vehicle rate and attitude performance. Furthermore, the behavior of the vehicle can be accurately predicted due to the simplicity of the structural configuration leading to a reduction of control model errors. The control system also benefits from this concept since most activity is centralized at the system center of mass.

The purpose of this study is to develop controllers for the proposed

Space Station and evaluate their performances to make recommendations for structural design and/or control alternatives.

ATTITUDE CONTROL

The problems of control for the Space Station have expensive solutions in cost and performance. As a preliminary guideline for the development of the Space Station proposed, the minimization of these control problems was a goal of high priority. To accomplish this objective, the flex frequency spectrum must be raised significantly to achieve desired separation between the flex and controller passband. Further, a configuration was sought that was relatively insensitive to operational activities. The configuration that resulted from these design guidelines is the triangular design studied here [Schneider,1982]. For the proposed station the flex spectrum begins at approximately 5.4 Hz. The controller passband, therefore, is sought to be placed below this frequency in order not to excite the flex modes of the structure.

To achieve this objective, the study is divided into the following three parts:

(1) Control system design
(2) Performance evaluation
(3) Experiments

The control system design assumes the rigidity of the Space Station and developes the lumped parameter controller for the rigid body model. The performance of this controller will be evaluated with the real system (represented by more complex model with the flexibility of structure incorporated). The designed controller will also be tested through the experiments using a physical model.

1. Control System Design

The flexible structures are so called distributed parameter systems and, accordingly, the distributed controls are required to maintain a desired profile of the structure. Since these controls are additional controls beside the controls for attitude and maneuvering, it is attempted to minimize the flexibility of the Space Station as much as possible and use only the lumped parameter controls for the presumed rigid body.

Two basic methods can be used to design control systems; each with their respective emphasis. The time-domain, state-space method used in modern optimal control theory emphasizes the performance of the vehicle. The frequency domain approach is used when stabiltiy issues are a concern of high priority. For the operational Space Station, performance requirements are low compared to other space vehicles while system stability is an important control obvjective. The frequency domain approach, however, is limited in general to simple systems and not readily applicable to multivariable control systems. On the other hand, the time-domain optimal control theory is well developed for multivariable control systems.

In this study, an attempt is being made to utilize the advantages of both approaches. For stability considerations, specifications are made in the frequency domain, and then the time-domain optimal control theory is applied to design the optimal controller gains. This hybrid method is so called the Inverse Problem [Park and Lee,1975] and it promises a bright future in the control system design of the Space Stations.

The Space Station model used to derive the control system design is the coupled three-axis Euler's equation, which is given by equating torques with inertia times acceleration as follows:

$$\begin{bmatrix} I_{xx} & I_{yx} & I_{xz} \\ I_{xy} & I_{yy} & I_{yz} \\ I_{xz} & I_{yz} & I_{zz} \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} T_{g_x} \\ T_{g_y} \\ T_{g_z} \end{bmatrix} + \begin{bmatrix} T_{\omega_1} \\ T_{\omega_2} \\ T_{\omega_3} \end{bmatrix} + \begin{bmatrix} T_{m_1} \\ T_{m_2} \\ T_{m_3} \end{bmatrix} + \begin{bmatrix} 0 & H_{T_3} & -H_{T_2} \\ H_{T_3} & 0 & -H_{T_1} \\ -H_{T_2} & H_{T_1} & 0 \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} + \begin{bmatrix} T_{d_x} \\ T_{d_y} \\ T_{d_z} \end{bmatrix} + \begin{bmatrix} T_{R_1} \\ T_{R_2} \\ T_{R_3} \end{bmatrix} \tag{1}$$

where:

I_{xx}, I_{yy}, I_{zz} - Principle axis inertias
I_{xy}, I_{xz}, I_{yz} - Cross axis inertias
$T_{g_x}, T_{g_y}, T_{g_z}$ - Gravity gradient torques
$T_{\omega_1}, T_{\omega_2}, T_{\omega_3}$ - Torques due to angular momentum changes
$T_{m_1}, T_{m_2}, T_{m_3}$ - Torques due to magnetics
$H_{T_1}, H_{T_2}, H_{T_3}$ - Angular momenta about the 3 axes
p, q, r - Body axis rates (roll, pitch, and yaw, respectively)
$T_{d_x}, T_{d_y}, T_{d_z}$ - "Disturbance" torques
$T_{R_1}, T_{R_2}, T_{R_3}$ - RCS firing torques

A model of the vehicle disturbance environment was determined to quantify the cyclic and non-cyclic torques. Also, for the proposed Station, solar inertial pointing is a necessary maneuvering requirement (approximately 0.06°/sec). Because of the predominant cyclic nature of the disturbance torques a momentum management scheme was devised using CMG's (control moment gyro's) and RCS (reaction control system). Additional control capability is also being sought by means of the Magnetic Torquers [Gran and Proise,1981; Liegeois,1970].

The three-axis model defined by Eq. 1 can be linearized and represented in the following matrix form:

$$\dot{x} = Ax + Bu + Cv \tag{2}$$

where x is the state vector of body axis rates and additional state variables representing the dynamics of CMG and Magnetic Torquers; u is the control vector of CMG commands, Magnetic Torquer voltage controls, and RCS commands; and v is the vector of disturbances which may include the gravity gradient torques and the aerodynamic torques.

The time-domain optimal control problem is defined to minimize the following performance functional

$$J = \int_0^\infty (x^TQx + u^TRu)dt \tag{3}$$

Solution of this optimal control problem gives the following optimal feedback control:

$$u = Kx \tag{4}$$

Note that the optimal feedback control gain matrix K will depend upon the choice of the weighting matrices Q and R of the performance equation (Eq. 3). This choice is arbitrary and subjective based upon engineering judgements. Here is where the Inverse Problem comes into the scene. The Inverse Problem is to make an optimal choice of the weighting matrices based upon the specifications in the frequency-domain which reflect the stability requirements.

2. Performance Evaluation

The control system design is based upon the rigid body assumption of the Space Station. Therefore, its performance requires evaluations when the controller is implemented in the real model of the Space Station. A Finite Element computer model for the Space Station was developed by using NASTRAN [Schneider,1982]. However, the model is complex and is not suitable for the evaluation purpose of the controller performance. It is necessary to develope a much simpler model which exhibit the same modal characteristics as the original NASTRAN model.

To meet this objective, a Parameter Estimation method is being developed. Using the data generated by the NASTRAN model of the Space Station, the Parameter Estimation algorithm will estimate parameters representing an equivalent but much simplified version of the Station model. The Parameter Estimation method is based upon the least squares method [Meyer and Lee,1982] and the modified Newton-Raphson method [Taylor and Iliff,1972]. It gives an iterative algorithm of the parameters in the direction of reducing the modeling error of a simplified model as compared to the NASTRAN model.

It is expected that an equivalent model will be represented by three plate equations coupled with rigid modules located at each corner of the triangle. Once this is completed, then other operational experiments can also be performed by attaching Remote Manipulator System, or by docking the Space Shuttle. The overall performance of the Space Station will then be evaluated by implementing the attitude controllers designed.

Additional use of the Parameter Estimation algorithm is its application on real data telemetered after the Space Station is put into operation. This feature will be very useful in estimating parameters of vehicle in orbit, especially the damping coefficients.

3. Experiments

In parallel with the analytical study, a scaled version of the Space Station is being built in NASA-JSC. This physical model will be hung and evaluated when the control system is implemented. It is hoped that the physical experiments give a new insight in control system design, structure characteristics, and instrumentations.

CONCLUSIONS

The purpose of this study was to develop controllers for the proposed Triangular Space Station and evaluate their performances to make recommendations for structural design and/or control alternatives. The control system design assumes the rigidity of the Space Station and developes the lumped parameter controller by using the Inverse Problem in optimal control theory. In order to evaluate the performance of the control system, a Parameter EStimation algorithm is being developed which will be used in modeling an equivalent Space Station model. Finally, a scaled version of the Space Station is being built for the purpose of physical experiments to evaluate the control system performance. Much of the work is still remains to be done continually.

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