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論　　文　　名	「Convex Optimization for Attitude, Vibration, and Orbit Control of a Spacecraft with Double-Gimbal Variable-Speed Control Moment Gyros」 （DGVSCMG 搭載宇宙機の凸最適化による姿勢・振動・軌道制御）
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論文要旨

Momentum exchange devices (MEDs) are popular actuators to control spacecraft attitude as they are electrically actuated and do not require fuel. MEDs consist of Control Moment Gyros (CMGs) and Reaction Wheels (RWs). RWs are often used for attitude control of satellites thanks to their mechanical simplicity, lower cost and simpler control law algorithms. However, RWs cannot respond to the demand of a high-speed attitude maneuver because they cannot provide both a high-speed wheel spin rate and large RW motor torque. The RW electrical power requirement is demanded to increase the rotor speed and reaches the limit of available power. Furthermore, there are mechanical limits to how fast a rotor can spin without causing structural issues. In contrast, CMGs are capable of producing large gyroscopic control torques onto the spacecraft which are proportional to the product of the rotor speed and the gimbal rate.

The challenges of CMGs are found in their increased mechanical complexity and control algorithm one as well as their increased device cost. There are various types of CMGs. Single-gimbal CMGs (SGCMGs) are the most common type of CMG devices. Here, the rotor is only able to gimbal about a single-body fixed frame to produce the desired control torque. A particular challenge of a SGCMG cluster is that they cannot always output the desired torque at singular gimbal configurations, often referred to as gimbal lock. Several singularity avoidance methods have been proposed. However, they tend to result in complexity of the algorithm and only approximately implement the desired control torque in the neighborhood of the singular configuration.

Single-gimbal variable-speed CMGs (SGVSCMGs) are a hybrid system which consists of a RW and an SGCMG. The extra degree of freedom (DOF) of the wheel spin rate enables SGCMGs to avoid the classical singularities at the cost of additional power and large rotor speed changes. On the other hand, double-gimbal CMGs (DGCMGs) can apply control torques

around arbitrary axes except for singular orientations corresponding to a gimbal lock, where both inner and outer gimbals coincide with each other. To avoid such a gimbal lock, large angular motions should not be commanded in one time. As a practical application, they have been used for the international space station (ISS) thanks to their ability to absorb large amounts of angular momentum. A double-gimbal variable-speed CMG (DGVSCMG) has two gimbal axes and a variable speed wheel. A DGVSCMG can generate large three dimensional torques if the wheel motor torque is adequately provided depending on the size of the DGVSCMG. This advantage realizes a high-speed attitude maneuver.

The satellite dynamics is described through a set of nonlinear differential equations. Most of recent studies about attitude control have used non-linear controllers such as Lyapunov function-based controllers. With Lyapunov function-based controllers, overall stability of attitude control is always guaranteed. However, the closed-loop control performance is not discussed in detail. To overcome this problem, we applied a gain-scheduled (GS) controller via linear parameter-varying (LPV) control theory with linear matrix inequalities (LMIs).

A variety of LPV control problems have been solved via LMIs under common Lyapunov functions. If one selects a common Lyapunov function for a whole operating range, the overall stability of the closed-loop system as time varying is guaranteed for any changing rate of the scheduling variable. However, selecting a common Lyapunov function for the whole operating range leads to conservatism of design. Many researchers have judged that this conservatism arises from selecting a common Lyapunov function and shifted their research into parameter-dependent Lyapunov functions. However, theory of parameter-dependent Lyapunov functions are more complicated and sometimes installed additional sufficient conditions or a line search parameter to make the problem convex. In addition, changing rates of scheduling variables are restricted in many cases. As a result, it has not been so useful for practitioners to use so far. To avoid such conservatism easily, this thesis discusses the post-guaranteed LMI method, in which the distinct Lyapunov solutions. Very few studies apply LPV control theory to attitude control of a spacecraft. Usually speaking, an LPV system for attitude control of a spacecraft needs many vertices to cover the whole operating range, which implies that LMIs cannot be simultaneously solved. Therefore, how to develop an easy-to-use LPV model is also an interesting topic for LMI researchers.

Simultaneous attitude and vibration control of a flexible spacecraft and simultaneous attitude and orbit control of an orbital spacecraft are of great interest in spacecraft applications. Missions of flexible spacecraft often require high-speed attitude maneuvers and high pointing accuracy and stabilization. Increasing mission power requirements has led to a recent trend in which communication satellites have large flexible solar battery paddles or communication antennas. From such mission requirements, a vibration control is also necessary to be considered as well as an attitude control. On the other hand, Halo orbits, in particular those in the Earth-Moon system, have been attracting attention for science and future human space exploration. Recently, such orbits are widely used by small or large satellites. However, such attractive orbits tend to be unstable. Therefore, stationkeeping is required to keep a satellite on the orbit. Then, a steering law for generating not only required torques but also required accelerations is important to be developed.

This thesis particularly focusses on DGVSCMGs as a new attitude actuator. First of all, this thesis develops an equation of motion (EOM) of a spacecraft with multiple DGVSCMGs. This is a generalized description of a spacecraft EOM with multiple MEDs, since DGVSCMGs include all MED functions such as RWs, SGCMGs, VSCMGs, and also DGCMGs. On the other hand, although jitter effects are often characterized through experimentation in order to validate requirements, it is of interest to include jitter in a computer simulation of the spacecraft in the early stages of spacecraft development. Therefore, fully-coupled dynamical jitter modeling of a spacecraft with imbalanced DGVSCMGs is also developed. Furthermore, a singularity of CMGs is analyzed and a singularity avoidance method is developed and discussed. Second, an LPV control theory and nonlinear/linear stability are introduced. Then, how to adapt an LPV control theory to the spacecraft attitude control problem is discussed. Next, attitude control of a spacecraft with a single DGVSCMG is considered while introducing an interesting parameter-dependent coordinate transformation. Here, a singularity analysis and a singularity-avoidance steering law using magnetic torquers (MTQs) are introduced. Additionally, two parallel DGVSCMG configuration is considered. By using such a configuration, an integrated power/attitude control system (IPACS) concept is adopted and also a fault-tolerant architecture is proposed. Finally, simultaneous attitude and vibration control and simultaneous attitude and orbit control are considered. A combined attitude and vibration controller using a dynamic inversion technique is proposed for a flexible spacecraft and a coupled attitude and orbit steering law of a spacecraft in Halo orbit is proposed.

審査結果の要旨

本論文では，DGVSCMG 搭載宇宙機の凸最適化による姿勢・振動・軌道制御について，様々な観点から幅広く研究を展開し，下記のような研究成果を得た．

（１） 宇宙機の新しい姿勢制御装置である DGVSCMG は，機構が複雑で，ダイナミクスの表現が煩雑であるが，複数の DGVSCMG が搭載された宇宙機の動力学方程式の一般表現を世界で初めて導出し，DGCMG，SGCMG，VSCMG，RW など多くの角運動量交換装置の様々な配置に対し，それらを搭載する宇宙機の動力学方程式の導出を容易にした．

（２） 宇宙機の姿勢制御のための状態方程式は，動力学方程式と運動学方程式から成り，動作点を表すスケジューリング変数が最低 6 個必要で，上限・下限を考慮すると，動作領域を凸包で覆った場合の端点数が 64 個となり，64 本の連立 LMI（線形行列不等式）を解かなければならず，従来は設計・運用が困難であった．本研究では，パラメータ依存基底変換・仮想状態変数という新たな概念を考案し，スケジューリング変数を見かけ上 3 個に減らすことで，LMI に基づく GS（Gain-Scheduled）制御器の設計・運用を容易にした．

（３） 1 基の DGVSCMG を例に，核空間をもたない駆動則の場合に，特異点回避機能をもつ制御則設計法を新たに考案し，その有効性を示した．DGVSCMG の 3 つのスケジューリング変数が球面座標系を構成することを指摘し，2 種類の凸包構成法を比較検討し，設計の簡単さと性能のトレードオフを示した．

（４） 2 基の DGVSCMG 搭載宇宙機で，正常時は 2 基の DGCMG モードで，異常時は 1 基の DGVSCMG モードで動作する耐故障アルゴリズムを新たに構築し，その有効性を示した．正常時に 2 基の DGVSCMG モードで生じる駆動則の核空間の自由度を用い，RW 駆動則で電力計画とホイール回転速均一化を行い，CMG 駆動則で姿勢制御と特異点回避を行う新しい駆動則を提案し，その有効性を示した．

（５）　柔軟構造物をもつ宇宙機の姿勢制御において，宇宙機の角加速度が柔軟構造物の振動方程式の仮想入力と見なせることに着目し，Dynamic Inversion を用いて柔軟モードの振動を抑制する姿勢制御方式を新たに考案し，その有効性を示した．

（６）　DGVSCMG とスラスタを用いて，宇宙機の姿勢制御と軌道制御を同時に実現する新たな駆動則を考案し，その有効性を示した．

以上の研究成果は，本研究分野に携わる多くの研究者に新たな示唆を与えるとともに，この研究分野の発展に大いに寄与するものであり，申請者が自立して研究活動を行うのに必要な能力と学識を有することを証したものである．学位論文審査委員会は，本論文の審査ならびに最終試験の結果から，博士（工学）の学位を授与することを適当と認める．