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|---|---|---|
| 氏　　名 | 神谷 俊夫 | |
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| 論 文 審 査 委 員 | 主　査 | 准教授 川勝 康弘 |
| | | 准教授 坂井 真一郎 |
| | | 教授　峯杉 賢治 |
| | | 名誉教授 土屋 和雄 京都大学 |
| | | 教授　小島 広久 首都大学東京 |
| | | 教授　松永 三郎 宇宙航空研究開発機構 |

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# 論文内容の要旨
## Summary of thesis contents

The recent evolution of advanced space missions such as deep space observation, earth observation, or disaster monitoring has been forwarded to higher “pointing accuracy” and higher “agility” in contradiction to the complexity of the structural design of the mission equipment required for the highly functionalized mission. The basic features which allow an efficient attitude maneuver are the spacecraft “pointing accuracy” and “agility”. Pointing accuracy represents the pointing stability after the maneuver. Fine pointing accuracy is realized by reducing the residual vibration where the vibration is induced during the maneuver motion and some remains after the maneuver. Thus the fine pointing accuracy can be rephrased as low residual vibration. Agility represents the rotational motion of the spacecraft with the fastest angular rate or shortest maneuver duration. The rotational motion is realized by attitude control actuators which are dimensioned according to the spacecraft's inertia and required maneuver performance etc. However every spacecraft has some limited resources, i.e. dimensional capability or mass capability or power consumption capability. Therefore the agility, meaning the flexibility and the ability to quickly move the satellite, becomes constantly constraint of the mission. The pointing accuracy and agility would sometimes be contrary requirements. If an agile motion is realized, then flexible structural modes of the spacecraft tend to be excited after the maneuver motion, and vice versa.

In contradiction to structural design being more complicated, demands for higher performances on pointing accuracy and agility are getting stronger and stronger for recent space applications. Nevertheless, looking around the conventional control algorithms, it is difficult to find the optimal control algorithm which realizes fine pointing and high agility when applied to spacecraft with complicated flexible structures. That is why this thesis deals with flexible spacecraft rest-to-rest maneuver in fine pointing accuracy and agile motion. Because satellite with large flexible structures contains many structural modes with various mode shapes and it is difficult to predict high-mode frequencies. Therefore not only multi-mode system but also the presence of unknown high-order flexible modes should be considered in high-accuracy controller design for actual satellite application.

This paper proposes control algorithms of flexible spacecraft especially for high-speed rest-to-rest maneuver with minimal residual vibration. The controllers presented in this paper are feedforward controllers composed of sinc functions as base function. It is demonstrated that these controllers show the highest performances among conventional controllers concerning the balanced performance of pointing accuracy and agility when applied to flexible spacecraft rest-to-rest maneuver especially for the system with unknown high-order flexible mode. The feature of the sinc function based feedforward controller is that the sinc function

itself has an ideal attenuation above a certain boundary frequency. Therefore when it is applied as base function of the controller, the characteristic frequencies of the flexible structures and the controller can be designed well separately. The concept of sinc function based controller is a new one, therefore the original sinc function based profiler called nil-mode-exciting profiler (NME profiler) presented in this paper is patented in Japan, US, and European countries.

In Chapter 4, comparisons of sinc function based smooth profilers to conventional input shapers and digital filtering techniques against single-mode system demonstrates that conventionally designed input shapers and frequency domain filters are less effective for command shaping than sinc function based smooth profilers. The original sinc function based smooth profiler, i.e. the NME profiler, were shown to offer performance advantage in terms of vibration reduction although rise time is less short than conventional input shapers although the ZVDDDDDD shaper shows the smallest residual vibration and the NME shows the second smallest vibration. When large modeling errors exist, the advantage of the sinc function based smooth profiler is very significant. These performance advantages are achieved because the sinc function based smooth profiler is designed to eliminate high frequency vibrations with higher attenuation level and have better robustness to modeling errors, compared to conventional input shapers and low-pass filters.

In Chapter 5, performance of the sinc function based smooth profiler has been compared to those of conventional on-off and smooth profilers using two-mode system including unknown high mode. The comparisons show that, in the presence of an unknown high-order flexible mode, conventionally designed on-off input shapers and smooth profilers are less effective in reducing vibrations than the smooth profiler based on sinc functions, even when identical durations are used. Only the smoothed bang-bang command shaped with ZVD shaper, i.e., hybrid-type profiler, shows similar level of small residual vibrations comparable with the smooth profiler based on sinc functions. When unknown high-order flexible modes with large mass exist, the advantage of the new smooth profiler is significant (more than an order of magnitude smaller residual vibration). These performance advantages are achieved because, as compared to conventional profilers, the new smooth profiler is specifically designed to eliminate high-frequency vibrations with higher levels of attenuation.

Chapter 6 introduces a new performance index, i.e. maneuver distance. Agility can be quantified once the input torque is restricted to some upper limit. Then comparison of agility performances of each conventional method discussed in the previous chapters is made in this chapter. Then, Chapter 7 proposes three kinds of improved sinc function based profilers for achieving higher agility. In Section 7.2, the conventional concept of convolution between smooth profiler and input shaper has been introduced and an equation to clarify a range where the convolved shaper has advantage in relation to command duration has been proposed. In Section 7.3, a new sinc function based smooth profiler to achieve higher agility: the sinc function convolved with step function has been proposed. Performances of the new profiler

have been compared with those of the original sinc function based profiler and conventional smooth/hybrid profilers. The sinc function convolved with step increased maneuver distance by a factor of 1.33 with comparable residual vibration under the same peak force condition, compared with the previously proposed sinc function based profiler (NME profiler). This profiler shows nearly equivalent maneuver distance but smaller residual vibration, compared with the conventional smooth profiler. In Section 7.4, another new sinc function based smooth profiler to achieve higher agility: the least-square fitted weighted sinc functions has been proposed. Performances of the new profiler have been compared with those of the sinc function based profilers mentioned in this thesis and conventional smooth/hybrid profilers. The sinc function based least-square fitted profiler increased maneuver distance by a factor of 2.28 under the same peak force condition, compared with the NME profiler. This profiler shows the longest maneuver distance and comparable or smaller residual vibration, compared with the ramped sinusoids or hybrid profilers. Both of the newly proposed sinc function based profilers can be used as effective alternatives for appropriate applications; if there are many unknown high-order flexible modes, the sinc function convolved with step would be suitable, if there are fewer critical high-order modes, the least-square fitted profiler would be suitable.

In Chapter 8, application of the proposed method to actual satellite program called ASTRO-G for which the NME profiler has been originally developed is presented. The effectiveness of the proposed method is confirmed by numerical simulation using actual designed flexible parameters of deployable antenna and solar array paddle. Experimental verifications to evaluate the effectiveness of the proposed algorithm is also referred here. The verification of the effectiveness of the proposed NME profiler to ASTRO-G application has been successfully done.

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# 博士論文の審査結果の要旨
# Summary of the results of the doctoral thesis screening

本論文は、柔軟構造物を有する宇宙機において高速な姿勢変更を行う場合に用いられる非励振プロファイラとして、Sinc関数に基づく“NMEプロファイラ”を新たに提案したものである。NMEプロファイラは、ある周波数以上の成分をほとんど含まないという特徴を持ち、このため、柔軟構造物が複雑でその振動モードの周波数に不確かさを有する場合にも、優れた非励振性能を発揮することができる。

論文は全八章からなる。第一章で研究背景が、第二章では提案手法の評価のために用いられる力学モデルの定義がなされた後、第三章でSinc関数に基づくNMEプロファイラの定式化およびその基本的な周波数特性の評価が示されている。また第四章では、まず周波数が既知の単一振動モードを有する力学モデルを用いた従来手法との比較検討が行われ、NMEプロファイラが従来手法と比べてもトップクラスの非励振性を有することが示されている。

従来手法の多くは基本的に、柔軟振動の周波数に合わせて設計されたプロファイラである。そのため、第四章のような場合には、従来手法であっても十分に良好な非励振性を発揮しうると考えられる。そこで第五章では、周波数既知の振動モードに加えて、周波数に不確かさを有する振動モードをも有する力学モデルを用いた評価が行われている。その結果、NMEプロファイラはこの周波数の不確かな高次モードに対しても優れた非励振性を示し、そのロバスト性が従来手法よりも優れたものであることが確認されている。

このようにNMEプロファイラはロバスト性に非常に優れた非励振性を示すが、その代償として、高速姿勢変更性では従来手法に対して必ずしも優位にはない。非励振性と高速姿勢変更性は基本的には相反する性能であって、一般にはトレードオフされる性能項目である。NMEプロファイラは、従って特に非励振性を重視するアプリケーションに適するものの、高速姿勢変更性も重要とされる場合にはそのままでは適用しがたい。そこで、まず第六章でアクチュエータトルク制約なども考慮した高速姿勢変更性の現実的な評価指標が定義された後、第七章で、NMEプロファイラの派生型２つが提案されている。これらはいずれも、オリジナルのNMEプロファイラと比べ、非励振性ではやや劣るものの高速姿勢変更性では優れるものである。また２つの派生型のうちでは、片方はより非励振性に優れ、他方はより高速姿勢変更性に優れるものである。比較検討の結果、２つの派生型プロファイラは、それぞれが対象とする非励振性と高速姿勢変更性のバランスにおいて、従来手法より優れた非励振性と高速姿勢変更性を両立することが明らかにされている。

第八章では、NMEプロファイラが実際の宇宙機に応用可能な手法であることの証左として、かつて実際の科学衛星姿勢制御系の一部としてNMEプロファイラが設計・評価された例が示されている。この衛星は大型展開アンテナを有していたため、柔軟振動周波数の変動に対するNMEプロファイラのロバスト性などが、高次モードまで含む詳細構造モデルを用いた評価により確認されている。第九章では論文全体が総括され、今後の課題が提示されている。

本論文ではこのように、まずSinc関数に基づくNMEプロファイラを提案し、特に周波数が不確かな高次柔軟モードを有する場合に優れた非励振性を発揮することを、従来手法との比較により示している。さらに、高速姿勢変更性を向上させた派生型のプロファイラ２つを提案することで、現実に求められる非励振性と高速姿勢変更性の幅広いバランスに対し、最適なプロファイラを提供することを可能としている。例えば合成開口レーダを搭載した地球観測衛星など、柔軟構造物を有しながらその姿勢を高速に変更したいという宇宙

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機のニーズは、今後増えてくるものと考えられる。本論文が提案するプロファイラは、そのような宇宙機にすぐにでも適用されうる実用性を有するものである。

以上、申請された論文は独自性・有用性を併せ持ち、博士論文に値するものとして、合格と判定した。