UNIVERSITI PUTRA MALAYSIA

H2 AND H∞ SATELLITE ATTITUDE CONTROLS FOR COMBINED ENERGY AND ATTITUDE CONTROL SYSTEMS

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By

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H_2 AND H_∞ SATELLITE ATTITUDE CONTROLS FOR COMBINED ENERGY AND ATTITUDE CONTROL SYSTEMS

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February 2015

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Combined Energy Storage and Attitude Control System (CEACS) is a new satellite system developed using flywheels to offer mass reduction, longer operation life and also cost reduction. To date, the demonstration of the CEACS attitude control performance has been limited only to the proportional derivative control (PD) and the active force control-proportional derivative (AFC-PD). Both controllers have their limitations where the PD controller is known to be less sensitive to uncertainties while the AFC-PD requires accurate in-situ measurement, which is not readily available at the moment. This proposed study will focus on improving the performance of small satellites with the CEACS system as the pitch attitude actuator by applying advanced control methods, H_2 control and H_∞ control. Both controllers were applied on three different classes of satellite, nanosatellite, microsatellite and enhanced microsatellite and simulated via MATLAB™ and SIMULINK® programming for the ideal and non-ideal scenarios. From the testing, it is found that the CEACS pitch attitude performance for both the H_2 control and H_∞ control can meet the required pitch attitude requirement of 0.2°. The comparison between both controllers shows that the H_2 control method has a slightly better pitch attitude performance compared to the H_∞ control for ideal and non-ideal scenarios. As for the comparison with the conventional PD controller and the PD-AFC controller, the results indicate that both the H_2 and H_∞ controllers outperform the conventional PD controller while having a slight advantage over the PD-AFC controller in terms of the attitude performance. However, as the feasibility of the AFC controller is highly dependent on the in-situ measurement of systems where the development of these systems requires time, thus the H_2 and H_∞ controls are the favourable control options for an immediate deployment of the CEACS system while providing an accurate pitch control in the face of orbit uncertainties.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Sarjana Sains

KAWALAN ATITUD SATELIT H_2 DAN H_∞ UNTUK SISTEM GABUNGAN TENAGA DAN KAWALAN ATITUD

Oleh

BAN YING SIANG

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Pengerusi: Profesor Renuganth Varatharajoo, PhD, Ir
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Sistem Kombinasi Penyimpanan Tenaga dan Kawalan Atitud Satelit (CEACS) adalah sistem baru yang direka untuk memberi pengurangan jisim satelit, memanjangkan tempoh hayat operasi dan juga penjimatan kos satelit. Sehingga hari ini, demonstrasi kecekapan CEACS dalam menangani fungsi kawalan atitud satelit hanya terhad kepada penggunaan kawalan derivatif berkadar (PD) dan kawalan tenaga aktif-derivatif berkadar (AFC-PD). Kawalan-kawalan ini mempunyai kelemahan masing-masing dimana kawalan derivatif berkadar kurang berkesan menangani masalah ketidakpastian. Kawalan tenaga aktif-derivatif berkadar pula memerlukan alat pengesan yang berfungsi di satelit yang memberikan pengukuran semasa, dimana perkembangan alat pengukuran tersebut memerlukan masa yang lebih. Kajian ini menitik berat aspek peningkatan kecekapan kawalan atitud satelit bersaiz kecil yang menggunakan CEACS sebagai penggerak paksi anggul melalui aplikasi cara kawalan maju, kawalan H_2 dan kawalan H_∞. Kedua-dua kawalan diaplikasikan dalam tiga kelas satelit yakni nanosatelit, mikrosatelit dan mikrosatelit maju dan semua ini dissimulasi melalui perisian komputer MATLAB™ dan SIMULINK® dalam sistem sempurna dan sistem tidak sempurna. Keputusan dari simulasi menunjukan bahawa kawalan anggul sistem CEACS dengan menggunakan kawalan H_2 dan kawalan H_∞ memenuhi keperluan misi iaitu ketepatan dalam 0.2° di paksi anggul. Perbandingan antara kedua-dua jenis kawalan menunjukan bahawa kawalan H_2 mempunyai kecekapan yang lebih baik daripada kawalan H_∞ dalam semua senario termasuk sistem sempurna dan sistem tidak sempurna. Perbandingan seterusnya dilakukan dengan kawalan PD dan kawalan AFC-PD. Keputusan perbandingan menunjukkan bahawa kedua-dua kawalan H_2 dan kawalan H_∞ adalah jauh lebih baik berbanding dengan kawalan PD, manakala dalam perbandingan antara kawalan atitud H_2 and H_∞ dengan kawalan AFC-PD, sedikit kelebihan dapat disaksikan. Walaubagaimanapun, disebabkan kebolehlaksanaan kawalan AFC adalah sangat bergantung kepada pengukuran semasa sistem di mana perkembangan alat pengukuran tersebut memerlukan masa yang lebih, maka kawalan H_2 dan

kawalan H_∞ merupakan pilihan yang baik di mana ia membolehkan pelaksanaan yang segera dalam sistem CEACS di samping mempunyai kawalan atitud dengan kejituan yang tinggi di samping ketidakpastian orbit.

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I certify that a Thesis Examination Committee has met on 5 February 2015 to conduct the final examination of Ban Ying Siang on his thesis entitled "H_2 and $H\infty$ Satellite Attitude Controls for Combined Energy and Attitude Control Systems" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This thesis was submitted to the senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the supervisory committee were as follows:

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LIST OF ABBREVIATIONS

M_x	Total external moment in body frame, X_B axis, Nm
M_y	Total external moment in body frame, Y_B axis, Nm
M_z	Total external moment in body frame, Z_B axis, Nm
$\dot{h}_I$	Time rate change of angular momentum vector in inertial frame, Nm
$\dot{h}_B$	Time rate change of angular momentum vector in body frame, Nm
I_x	Satellite roll moments of inertia in body frame, Kgm^2
I_y	Satellite pitch moment of inertia in body frame, Kgm^2
I_z	Satellite yaw moments of inertia in body frame, Kgm^2
ω_x	Satellite roll angular velocity in body frame, X_B axis, $rads^{-1}$
ω_y	Satellite pitch angular velocity in body frame, Y_B axis, $rads^{-1}$
ω_z	Satellite yaw angular velocity in body frame, Z_B axis, $rads^{-1}$
$\dot{\omega}_x$	Satellite roll angular acceleration in body frame, X_B axis, $rads^{-2}$
$\dot{\omega}_y$	Satellite pitch angular acceleration in body frame, Y_B axis, $rads^{-2}$
$\dot{\omega}_z$	Satellite yaw angular acceleration in body frame, Z_B axis, $rads^{-2}$
T_C	Control Torque, Nm
T_D	Disturbance Torque, Nm
ω_{BI}	Inertial angular velocity of a satellite in body frame with respect to inertial frame, $rads^{-1}$
ω_{BR}	Angular velocity of the body axis frame with respect to the orbit reference axis frame, $rads^{-1}$
ω_{RI}	Angular velocity vector of the orbit reference axis frame with respect to inertial axis frame, $rads^{-1}$
θ	Pitch angle in body frame, rad
Φ	Roll angle in body frame, rad

ψ	Yaw angle in body frame, rad
p	Angular rate in body frame, $rads^{-1}$
q	Angular rate in body frame, $rads^{-1}$
r	Angular rate in body frame, $rads^{-1}$
i	Unit vectors of orbit reference frame
j	Unit vectors of orbit reference frame
k	Unit vectors of orbit reference frame
ω_0	Angular orbital velocity of satellite, $rads^{-1}$
$\vec{r}$	Radius vector in orbital frame, m
$\vec{v}$	Velocity vector in orbital frame, ms^{-1}
R_x	Radial vector from satellite to center of mass of Earth in body frame, km
R_y	Radial vector from satellite to center of mass of Earth in body frame, km
R_z	Radial vector from satellite to center of mass of Earth in body frame, km
R_0	Distance from center of mass of earth to satellite = R_{earth} + R_{orbit} km
R_{orbit}	Distance from surface of earth to satellite, km
R_{earth}	Earth radius = 6378 km
G_x	Gravity gradient moment in body frame, Nm
G_y	Gravity gradient moment in body frame, Nm
G_z	Gravity gradient moment in body frame, Nm
ρ	Radius vector from the body center of mass to a generic mass element,dm
m	Mass, kg
μ	The gravitational parameter = $3.989\times10^{14}m^3s^{-2}$
k_R	Unit vector of orbit reference frame axis.

$A_{\psi\theta\Phi}$	Rotational matrix from ψ to θ to Φ (axes order of rotation 3→2→1)
I_w	Flywheel inertia, kgm^2
K	motor/generator torque constant
τ_w	System response time =2s
$T^{S/w1}$	projection matrix of first flywheel from satellite coordinate frame to flywheel coordinate frame = 1
$T^{w1/S}$	projection matrix of first flywheel from flywheel coordinate frame to satellite coordinate frame = 1
$T^{S/w2}$	projection matrix for the second flywheel from satellite coordinate frame to flywheel coordinate frame = -1
$T^{w2/S}$	projection matrix for the second flywheel from flywheel coordinate frame to satellite coordinate frame = -1
T_{cmd}	Torque attitude command, Nm
T_y	Torque exerted on satellite body, Nm
Q_{sat}	Satellite pitch attitude, rad or °
P	CEACS Plant matrix
Z	Output from plant
y	Measured outputs
U	Control inputs, Nm
W	External inputs including disturbance
W1	Weighting matrix on plant output
W2	Weighting matrix on plant control input
A	System matrix
B_1	External input matrix
B_2	Control input matrix
C_1	Controlled output state matrix
C_2	Measured output state matrix
D_{11}	Controlled output external Input matrix

CHAPTER 1

INTRODUCTION

Since the beginning of human civilization, man has always marvelled at the beauty of the celestial sky. Years of observations of the celestial bodies such as the Sun, Moon and stars had led to the discovery of some principle laws of nature that have helped in the development of mankind. One of the oldest applications of a celestial body developed was for navigations. Understanding the position of the sun and stars during the day and at night time had become a useful reference for mankind in exploring the land of the unknown and thus expanding human reach and building bridges connecting to the other parts of the world. Through the tireless efforts of scientists for many centuries, much change has been seen in our perceptions and knowledge of the physics behind the observations of celestial bodies. From a space model where the Earth is deemed as the center of the universe, surrounded by revolving celestial bodies as suggested by Aristarcus (310-250 B.C); it had evolved and improved to a modern space model that was first suggested by Coppernicus in 1543 where Sun is seen as the center of the Solar system with Earth and planets revolving around it (Vallado, 2001). Later, much effort was put into the motion and kinetics of celestial bodies, notably by Kepler, who described the motion of planets through three Keplers's laws in 1619 and Isaac Newton on the dynamics of motion via three Newton's Laws in 1687 (Vallado, 2001). The new laws developed laid a strong foundation for scientists to improve and these laws were used primarily to accurately predict the motion of celestial bodies. It was not until several hundred years later when humans started to dream of utilizing space resources with the advancements in electronics and rocket technology. Fuelled by the political environment during the Cold War, the race to space between the United States and the Soviet Union had led to the launch of the first man-made satellite, "Sputnik" by the Soviet Union on October 4, 1957. Since then, satellites have been used in many fields such as telecommunications, meteorology, scientific research, and others (Sidi, 2000). According to a survey study conducted by Futron Corporation (2012) in May 2012, there are up to 994 satellites in various orbits and functions currently operational globally. Review on the past decades also showed that satellite demand remains high where there has been a growth of 175% in terms of global satellite industry revenues from 2001 to 2011 (Futron Corporation, 2012). According to Aragón, Mura, Dionisio, Howes, & Erickson (1998), to ensure the growth of space revenue, cost reduction and increased performance in the space industry are essential. The same study above also pointed out that spacecraft, launcher and launch service itself contribute from 20% to 50% of the total cost. Thus, the ability to reduce the cost in these areas will help to ensure a lower cost to the revenue ratio, which in turn encourages the usage of satellites for the consumer market. With the advancement in technology, cost reduction has become possible with the introduction of hybrid subsystems that combine power storage and attitude control as proposed by several authors (Roithmayr, 1999; Tsiotras, Shen, & Hall, 2001; Varatharajoo & Fasoulas, 2002). The system uses flywheel as an attitude control actuator as well as an energy storage mechanism (Tsiotras et al., 2001). The introduction of flywheel is seen as a better alternative to batteries, which is the conventional method of storing and supply the electrical energy produced by solar panels while flywheel has better performance in terms of longevity, lower mass requirement, wide operational temperature range, and capable of controlling attitude and energy storage simultaneously (Ginter et al., 1998). Following this, a full system design and numerical treatment of a Combined Energy and Attitude Control System (CEACS) for small satellites was presented by Varatharajoo in his work (Varatharajoo & Fasoulas, 2002). As pointed out by Won (1999), gravitational, aerodynamic and magnetic torques are part of the external disturbance that will affect the satellite attitude. In order to maintain the pointing accuracy of a satellite under the influence of external disturbances, a suitable attitude controller will need to be designed. Although further studies by Varatharajoo and his team had demonstrated that CEACS using proportional-derivative (PD) control and active force control-proportional-derivative (AFC-PD) control are able to meet the specified mission requirements and provide adequate control to maintain and control the attitude of a satellite (Varatharajoo, 2004, 2006; Varatharajoo, Wooi, & Mailah, 2011), it is worthwhile to explore the other control methods to provide a complete comparative review of the control methods available in its implementation of CEACS. The purpose of the research presented in this thesis is to focus on developing and implementing several different control methods for attitude controls in small satellites via combined energy storage and attitude control system (CEACS).

1.1 Problem Statement

CEACS will be the ideal solution for the next generation satellite, which will offer mass reduction, longer operation life and also cost reduction. To date, the attitude control performance of CEACS has been demonstrated using PD and AFC-PD controller. Although both controllers are able to meet the desired satellite mission requirement; however there is still room for improvement. The PD controller is less sensitive to uncertainties in general whereas the AFC-PD requires accurate in-situ measurement which is not readily available at the moment. Thus, there is a need to have a complete analysis of the attitude pointing performance of CEACS using other control methods that are robust in handling uncertainties and can be applied immediately into CEACS. All controllers will then be compared and served as a reference for future implementation in satellite applications.

1.2 Research Objectives

As mentioned previously, only the PD and AFC-PD controls have been investigated for CEACS system in small satellites. The purpose of this research is to design and implement different control methods for the CEACS pitch attitude control. A small satellite CEACS model will be proposed based on an earlier work done by Varatharajoo (2004), whereby three types of satellite models are investigated, e.g., nanosatellite, microsatellite and enhanced microsatellite.

1.3 Research Scope

The research scopes are:

i) Developing the CEACS pitch attitude control architecture for the H_2 and H_∞ controllers.

ii) Performing numerical evaluation on the developed CEACS H_2 and H_∞ based attitude control architectures.

iii) Optimising the CEACS attitude control performances for both controllers.

1.4 Thesis Contribution

The research will focus on the pitch attitude control performance of CEACS in small satellites. This study will be able to refine the attitude control performance of CEACS via the proposed controllers. At present, only the PD and AFC-PD controllers have been tested for CEACS. The CEACS pitch attitude performance using optimal and robust controllers such as H_2 controller and H_∞ controller could provide a much better CEACS attitude control capability. Comparison on the pitch attitude control between the proposed controllers and the controllers studied in the past will also serve as a reference for the CEACS implementation.

1.5 Outline of Thesis

The thesis is presented in six chapters including this chapter, namely, literature review, methodology, simulation and results, discussions, and conclusion and recommendations. In Chapter 2, the literature review, all the essential background information will be discussed for a better understanding of the research topic. The information includes the satellite dynamics, the standard attitude control systems, flywheel development and the review on past research work on CEACS. Chapter 3 will demonstrate the methodology for the research where the numerical treatment to CEACS model and explanation on the CEACS simulation algorithm are presented. This will be followed by Chapter 4, which presents the reference mission and subsequently the simulation and result done via MATLAB™ and SIMULINK® for the H_2 and H_∞ controllers applied on CEACS in nanosatellite, microsatellite and enhanced microsatellite. The non-ideal scenarios are treated and shown as well in the chapter. Chapter 5 discusses the performance of the controllers for CEACS and also provides a comparison with other controllers done in other literature. Finally, the conclusion and recommendation on the optimal controllers based on all satellite scenarios are given in Chapter 6.

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