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DYNAMICS OF A FLEXIBLE TETHERED SATELLITE SYSTEM IN THE PRESENCE OF AERODYNAMIC DRAG AND GRAVITY GRADIENT

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DYNAMICS OF A FLEXIBLE TETHERED SATELLITE SYSTEM IN THE PRESENCE OF AERODYNAMIC DRAG AND GRAVITY GRADIENT

By

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DYNAMICS OF A FLEXIBLE TETHERED SATELLITE SYSTEM IN THE PRESENCE OF AERODYNAMIC DRAG AND GRAVITY GRADIENT

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June 2017

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Tethered Satellite System (TSS) has emerged as one of the main topics of discussion in the aerospace research field. However, most research works focus more on the rigid tether as compared to a flexible structure. In this thesis, three different material types utilized by a flexible tether are examined and compared with the common rigid tether. In addition, the air drag perturbation will be taken into consideration as the entire TSS is flown around the Low Earth Orbit (LEO) region where air-drag perturbation is a dominant factor. Subsequently, a survival analysis was performed. In addition, the gravitational force dynamic models as developed by Urrutxua, Peláez, and Lara are incorporated into the TSS model to analyze the stability for both rigid and flexible cases.

Based on the numerical analysis, tungsten showed a better dynamic performance in terms of having the lowest hazard ratio reading, but Spectra-2000 showed to be the strongest in terms of tension performance, with a maximum tension force of 66 447 N and 43 298 N before snapping for a flexible tether in a non-coplanar model with and without drag, respectively. Albeit $\sigma > 0.75$, which exceeded the critical value, the TSS can be stabilized by varying the primary mass, M_1, in an order of 10^{20} kg and the total tether length, L, under a specific condition. Nevertheless, the two-link flexible TSS is stabilized by utilizing the piecewise controllers and a total tether length of 700 m was deployed and maintained after a period of 450 seconds.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

DINAMIK SISTEM TETHER SATELIT YANG FLEKSIBEL DENGAN KEHADIRAN GANGGUAN DAYA SERET AERODINAMIK DAN GRADIEN GRAVITI

Oleh

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Pengerusi: Profesor Renuganth Varatharajoo, PhD
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Sistem satelit menggunakan *tether* merupakan salah satu topik utama yang kerap dibincangkan dalam bidang penyelidikan aeroangkasa. Walaubagaimanapun, kebanyakan kerja penyelidikan memberi tumpuan lebih kepada tali *tether* yang tegar berbanding dengan struktur fleksibel. Oleh itu, dalam tesis ini, satu perbandingan di antara bahan *tether* yang digunakan dalam aplikasi *tether* yang fleksibel dan juga dengan tali *tether* jenis yang tegar akan dikaji. Sistem satelit terikat fleksibel yang diuji terdiri daripada tiga jasad tegar yang dihubungkan dengan dua *tether* fleksibel. Tiga jenis bahan yang dilihat berpotensi digunakan untuk membuat tali tether dicadangkan sebagai bahan rujukan. Di samping itu, faktor geseran udara atau "*air-drag*" akan diambilkira dalam penyelidikan ini disebabkan *tether* ini diterbangkan di persekitaran orbit rendah bumi, di mana gangguan geseran udara adalah dominan.

Selain itu, model dinamik graviti yang dikaji oleh Urrutxua, Peláez dan Lara akan diambil kira dalam model *tether* jenis tegar bagi membuat analisa kestabilan untuk kedua-dua applikasi tether jenis struktur yang tegar dan fleksibel. Satu sempadan kawasan kestabilan telah dibentuk untuk model *tether* yang tegar dan kawalan yang terdiri daripada kawalan *squared sigma* dan controller menggunakan *backstepping* direka khas untuk menstabilkan dua *tether* jenis fleksibel. Berdasarkan keputusan simulasi yang diperolehi, tungsten menunjukkan prestasi yang terbaik dari segi nilai bacaan nisbah bahaya, tetapi Spectra-2000 merupakan bahan yang paling kuat dari segi ketegangan. Selain itu, didapati bahawa nilai σ bagi sistem satelit menggunakan tether tegar yang melebihi nilai kritikal 0.75 boleh distabilkan dengan mengubah jisim utama, M_1, dalam lingkungan 10^{20} kg dan juga kepanjangan tether, *L*, dalam keadaan yang tertentu. Namun, sistem satelit dua-link menggunakan *tether* fleksible dapat dikawal dengan menggunakan kawalan *squared sigma* dan *backstepping*. Kepanjangan tali *tether* sebanyak 700 m berjaya dilepaskan dan dikekalkan untuk tempoh sepanjang 450 saat waktu fasa *station keeping*.

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APPROVAL

I certify that a Thesis Examination Committee has met on 9 June 2017 to conduct the final examination of Aaron Aw Teik Hong on his thesis entitled "Dynamics of a Flexible Tethered Satellite System in the Presence of Aerodynamic Drag and Gravity Gradient" 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 Doctor of Philosophy.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

M_1	Mass of primary satellite 1 [kg]
M_2	Mass of secondary satellite 2 [kg]
M_c	Mass of central satellite [kg]
M_{T1}	Mass of the tether 1 [kg]
M_{T2}	Mass of the tether 1 [kg]
r_{T1}	Radius of tether 1 [m]
r_{T2}	Radius of the tether 2 [m]
θ	True Anomaly [deg]
ϕ	Out-of-plane Angle [deg]
ψ	In-plane Angle [deg]
$\dot{\phi}$	Rate of change of out-of-plane Angle [deg/s]
$\dot{\psi}$	Rate of change of in-plane Angle [deg/s]
L	Total Length of the tether [m]
$\dot{L}$	Rate of change of tether length [m/s]
ω	Orbital Angular Velocity [deg/s]
e	Eccentricity
μ	Standard Gravitational Parameter [m^3/s^2]
μ_1	Primary Mass Gravitational Parameter [m^3/s^2]
μ_m	Reduced mass [m^3/s^2]
υ	Lattitude Angle of each Tether element, dM [deg]
dM	Tether element

P_w	Legendre Polynomial
C_n	Ultraspherical Polynomial
J_w	Zonal Harmonics
γ_C	Lattitude Angle of Tether's Center of Mass [deg]
E	Young Modulus [GPa]
ρ	Tether Linear Density [kg/m^3]
A	Area of Tether [m^2]
d_T	Diameter of Tether [m]
I_n	Moments of Inertia for Tether
q_1	Axial Vibration Modal Coordinates
q_2	Transverse Vibration Modal Coordinates
q_3	Lateral Vibration Modal Coordinates
T_n	Kinetic Energy with respect to n-body [J]
U_n	Potential Energy with respect to n-body [J]
T_n	Tension in Tether [N]
Q_θ	Air Drag Torque on In-Plane Angle
Q_ϕ	Air Drag Torque on Out-of-Plane Angle
τ	Torque from motor [N.m]
C_d	Air-Drag Coefficient
ρ_o	Atmospheric Density [kg/m^3]
h	Altitude [km]
h^*	Height Characteristics [km]
$\mathbf{v_a}$	Air Molecules Velocity [m/s]
Υ	Flight Path Angle [deg]

$\boldsymbol{M}_{\mathrm{T}}$	Moment of Tether
$\hat{\rho}$	Position vectors of mass bodies
φ	Angle of attack [deg]
Z_{+}^{k}	Nonnegative integers
R	Real numbers
R^{k}	k-dimensional real linear space
$\otimes$	Kronecker product
I	Identity Matrix
C	Complex numbers
V	Lyapunov function candidate
x, y, z	Relative position of tethered subsatellite

CHAPTER 1

INTRODUCTION

1.1 General Overview

There are two main areas of focus in this research. The first was to investigate which tether material is durable enough for survival under the perturbation of aerodynamic drag forces when the tethered satellite system (TSS) is flying at Low-Earth Orbit below 500 km. Next, we conducted a thorough stability analysis on the TSS when it was flown above 500 km but well within the LEO region which housed the effects of gravity gradient. Our task was to control the deployed tether length by utilizing a specially designed controller. Prior to this, many research works were done on the flexible tether that provided a reasonable understanding and accuracy on the tether dynamics of the system (Misra & Modi, 1982). The types of materials used for a space tether must be in accordance to the types of applications it is based on. It would be most certainly useful for tether designing to fully understand the material types best suited for a certain mission while being subjected to environmental effects (Silverman, 1995). Various tests were also carried out to determine the hypervelocity impact of space debris on the types of materials prior to flight, while excluding the effects of air-drag (Sabath & Paul, 1997).

1.2 Problem Statement

Based on most literature works, air-drag or air-resistance is usually not considered in order to simplify the complexities of the system dynamics. Therefore, if we were to accurately model an actual tethered satellite system (TSS) operating around the LEO region, the effects of air-drag should be considered as a variable because air drag is highly dominant especially when flying around 300 km (Johnson, Gilchrist, Estes, & Lorenzini, 1999). In addition, the majority of the tethered satellite system (TSS) consists of a two – body system and both were usually assumed to be point-mass or modelled as particles (Mankala and Agrawal, 2005; Woo and Misra, 2013; Zhong and Zhu, 2013).

Moreover, the study on the stability of a TSS is crucial for missions such as microgravity level evaluation in a TSS. There are many research works focusing on the tether deployment stability alone, but most of them consider the satellites to be in point mass and not a rigid body. It was found that the critical value, σ must not exceed 0.75 to ensure the stability of the TSS (Jesus, 1995). The study on the gravitational actions on the TSS was investigated when the TSS flew more than 500 km within the LEO, but no one conducted a stability analysis (Urrutxua et. al., 2015). It was noted that in order to analyze the stability of the TSS, many sources cited commonly adopted methods such as the Hamiltonian approach in obtaining the Lyapunov function, but these methods failed to explain how the exact Lyapunov function was being formulated as the data was attained on a trial and error manner. Some attached thrusters to stabilize the TSS during deployment.

However, as the most convenient option, thrusters brought about unnecessary high costs (Mantellato, Valmorbida, & Lorenzini, 2015). The problem statements of this research are:

a) The aerodynamic drag is dominant within the Low-Earth Orbit (LEO) region at an altitude below 500 km and this perturbation would affect the survivability of the space tether.

b) In analyzing the stability of the rigid TSS for a sigma value that exceeds the critical value of 0.75, it is extremely difficult in determining a suitable Lyapunov candidate utilizing the standard energylike function approach due to the highly non-linear system of the TSS dynamics.

c) The two-link flexible TSS is very unstable during the deployment phase in the presence of gravity-gradient and numerous known control methods were adopted in order to stabilize the system, but fail in controlling the exact amount of tether length being deployed for station-keeping purposes.

1.3 Objective

This thesis aims to address and solve issues pertaining to a flexible (TSS) while taking into consideration external disturbances. The specific objectives of this research are:

a) To determine which material is suitable for a space tether that is flying in Low-Earth Orbit (LEO) below 500 km with the effects of air-drag perturbation and to analyze the critical value, σ for a rigid TSS.

b) To design a sigma square controller to stabilize both the in-plane and out-of-plane angles of the flexible TSS during the deployment phase when flying in LEO above 500 km with regards to the effects of gravity gradient.

c) To design a backstepping controller to control the deployed tether length as part of the station keeping phase when flying in

LEO above 500 km while keeping in consideration the effects of gravity gradient.

Therefore, for this research, we utilized the Carleman Linearization Theorem; a method that converts a finite nonlinear system to an infinite linear system that will give us a systematic approach in obtaining the Lyapunov function which has not been use before in this area of expertise. Since the TSS is being examined by utilizing a flexible tether, we designed a suitable piecewise controller that utilizes the square sigma and backstepping controller method in stabilizing both the in-plane and out-of plane angles of the TSS during its deployment phase in LEO at an altitude above 500 km where gravity gradient acts as an external force. As this experiment has never been conducted before, the following section will contain further discussions and elaborations (Modi, Pradhan, & Misra, 1997; Decou, 1989; Banks & Hernandez, 2005; Mantri, Mazzoleni, & Padgett, 2007; Zhao, Cai, & Qi, 2010).

1.4 Scope and Limitations of Study

A comparison was made between a coplanar and a non-coplanar model for both the rigid and flexible tethers regarding the tether tension for three material types that are being tested. Subsequently, a survival probability analysis was conducted for the tether's three types of materials while under the effects of air-drag perturbation and comparisons were made when the TSS flew at two different altitudes.

The primary focus of this research is to design a specialized piecewise controller which could switch from a tether deployment phase to a station keeping phase while controlling the length of the flexible TSS. New techniques will be introduced in designing the controllers to stabilize the system. The Carleman Linearization and Lyapunov methods will be utilized in assessing the stability of the TSS while Matlab® and Mathematica software programs will be used to conduct the numerical analysis.

There are a few limitations from the research work presented in this thesis. The main objective which is to decide the types of material best utilized for a space tether subjected to the Low-Earth Orbit (LEO) environment is only limited to three. Also, in analyzing the critical value, σ for a rigid TSS, the simulation for this analysis is simulated in a non-asteroid condition. As such, the primary mass could be varied without restriction. This may not be applicable when simulated for a colossal body with a fixed mass such as an asteroid. Lastly, when designing the piecewise controller for a two-link flexible TSS, this research focused only on controlling the deployment and station-keeping phase without considering the retrieval phase.

1.5 Thesis Outline

This thesis consists of six chapters. The outlines are as follows:

Chapter 1 provides an overview about the past works that have been conducted regarding the tethered satellite system in general. The problem statement, research objectives and scope of study are also included in this chapter.

Chapter 2 reviews the literature on the history of TSS and also covers the many types of TSS applications in space. A description on the tether space environment, specifically on the Low-Earth Orbit (LEO) region is also described in this chapter.

Chapter 3 provides a detailed description on the mathematical modeling of the TSS dynamics for both coplanar and non-coplanar model. The process in designing the backstepping controller is also elaborated fully here.

Chapter 4 provides the results obtained from the simulation of the TSS dynamics regarding tether materials selection, flexible tether deployment and the station-keeping phase. Attained results will be discussed generally.

Chapter 5 focuses on the numerical analysis of the data obtained from the TSS dynamics simulation. A full discussion will be provided as well
Chapter 6 concludes the research work and includes some suggestions for future research.

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