# MASS REDUCTION OF A CONCEPTUAL MICROSATELLITE ALUMINUM STRUCTURE VIA EMPLOYING PERFORATION PATTERNS

By

SARMAD DAWOOD SALMAN DAWOOD

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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## DEDICATION

This work is dedicated
to
My dear wife, **Halah** and two boys, **Ahmed** and **Aws**,
for all the hardships they endured during more than five years of study
The memory of my dear **Father**, for his inspiration
The memory of my dear **Mother**, for her support
My dear sister, **Sana**, and my extended **Family**, for all their support
My Dear **Friends**, for their help and support

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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**Chairman : Associate Professor Ir. Mohammad Yazdi bin Harmin, PhD**
**Faculty : Engineering**



Mass reduction is a primary design goal pursued in satellite structural design, since the launch cost is proportional to their total mass. The most common mass reduction method currently employed is to introduce honeycomb structures, with space qualified composite materials as facing materials, into the structural design, especially for satellites with larger masses. However, efficient implementation of these materials requires significant expertise in their design, analysis, and fabrication processes; moreover, the material procurement costs are high, therefore increasing the overall program costs. Thus, the current work proposes a low-cost alternative approach through the design and implementation of geometrically-shaped, parametrically-defined metal perforation patterns, fabricated by standard processes. Four geometric shapes (diamonds, hexagons, squares, and triangles) were designed parametrically, and hence implemented onto several components of a structural design for a conceptual sub-100 kg microsatellite. Subsequently, a parametric design space was defined by developing two scale factor and also two aspect ratio variations on the four baseline shape designs. The change in the structure's fundamental natural frequency, as a result of implementing each pattern shape and parameter variation, was the selection criterion, due to its importance during the launcher selection process. The best pattern from among the four alternatives was selected, after having validated the computational methodology. This validation was achieved through implementing experimental modal analysis on a scaled-down physical model of a primary load-bearing component of the structural design. The selected pattern design was hence refined iteratively, to yield the same value of fundamental natural frequency, but with significant mass reduction. From the findings, a significant mass reduction percentage of 23.15%, from 84.48 kg to 62.42 kg, utilizing the proposed perforation concept, was achieved in the final parametric design iteration. This reduction was relative to the baseline unperforated case, while maintaining the same fundamental natural frequency. Dynamic loading analyses were also performed, namely, quasi-

static, random, and shock loading analyses, utilizing both the baseline and the finalized perforated designs. These analyses investigated the contrast in the capabilities of the two design to withstand the nominal dynamic launch loads. The findings showed that the final perforated design did have the capacity to withstand the launch loads without yield failure, as indicated by the computed positive yield margins of safety for each loading type. With these encouraging outcomes, the perforated design concept proved that it could provide an opportunity to develop low-cost satellite structural designs with reduced mass, and with reasonably good structural performance.

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

**PENGURANGAN JISIM BAGI STRUKTUR ALUMINIUM MIKROSATELIT KONSEP DENGAN MENGGUNAKAN CORAK LELUBANG**

Oleh

**SARMAD DAWOOD SALMAN DAWOOD**

**Julai 2022**

**Pengerusi : Profesor Madya Ir. Mohammad Yazdi bin Harmin, PhD**
**Fakulti : Kejuruteraan**

Pengurangan jisim adalah matlamat reka bentuk utama yang dijalankan dalam reka bentuk struktur satelit, kerana kos pelancaran adalah berkadaran dengan jumlah jisimnya. Kaedah pengurangan jisim yang paling biasa digunakan pada masa kini adalah dengan menggunakan struktur sarang lebah, berserta bahan komposit yang layak angkasa sebagai bahan muka, ke dalam reka bentuk struktur, terutamanya bagi satelit dengan jisim yang lebih besar. Walau bagaimanapun, pelaksanaan secara cekap bagi bahan-bahan ini memerlukan kepakaran yang ketara dalam reka bentuk, analisis, dan proses fabrikasinya; tambahan pula, kos perolehan bahan adalah tinggi, justeru itu meningkatkan kos keseluruhan program. Maka, kerja semasa mencadangkan pendekatan alternatif yang berkos rendah melalui reka bentuk dan pelaksanaan corak lelubang logam berbentuk geometri, ditakrifkan secara parametrik, yang difabrikasi secara proses standard. Empat bentuk geometri (berlian, heksagon, segiempat sama dan segitiga) telah direka bentuk secara parametrik, dan seterusnya dilaksanakan pada beberapa komponen reka bentuk struktur bagi konseptual mikrosatelit sub-100 kg. Seterusnya, ruang reka bentuk parametrik ditakrifkan kepada dua faktor skala dan juga dua variasi nisbah aspek terhadap empat reka bentuk bentuk dasar. Perubahan dalam frekuensi asli asas struktur, hasil daripada pelaksanaan setiap bentuk corak dan variasi parameter, adalah merupakan kriteria pemilihan, disebabkan kepentingannya semasa proses pemilihan pelancar. Corak yang terbaik dikalangan empat alternatif ini kemudiannya telah dipilih, setelah metodologi pengiraannya disahkan. Pengesahan ini dicapai melalui pelaksanaan analisis modal eksperimen pada model fizikal yang diskala-kecilkan bagi komponen galas beban utama reka bentuk struktur. Reka bentuk corak yang dipilih telah diperhalusi secara lelaran, bagi menghasilkan nilai frekuensi asli asas yang sama, tetapi dengan pengurangan jisim yang masih ketara. Daripada penemuan, peratusan pengurangan jisim yang ketara sebanyak 23.15%, daripada 84.48 kg kepada 62.42 kg, menggunakan konsep lelubang yang dicadangkan, telah dicapai

dalam lelaran akhir reka bentuk parametrik. Pengurangan ini adalah relatif terhadap kes dasar tanpa lelubang, disamping mengekalkan frekuensi asli asas yang sama. Analisis pemuatan dinamik juga dilaksanakan, iaitu, bebanan kuasi-statik, rawak dan hentakan, dengan menggunakan kedua-dua reka bentuk dasar dan reka berlelubang yang dimuktamadkan. Analisis ini menyiasat perbezaan dalam keupayaan kedua-dua reka bentuk dalam menahan beban pelancaran dinamik nominal. Hasil penemuan menunjukkan bahawa reka bentuk berlelubang akhir sememangnya mempunyai kapasiti untuk menahan beban pelancaran tanpa kegagalan alah, seperti yang ditunjukkan oleh margin alah keselamatan yang positif yang dikira bagi setiap jenis pemuatan. Dengan hasil yang menggalakkan ini, konsep reka bentuk berlelubang membuktikan bahawa ianya boleh membuka peluang bagi membangunkan reka bentuk struktur satelit kos rendah dengan jisim yang dikurangkan, dan dengan prestasi struktur yang cukup baik.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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This is to confirm that:
- the research conducted and the writing of this thesis was under our supervision;
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TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

## LIST OF APPENDICES

## LIST OF ABBREVIATIONS

| | |
|---|---|
| 3D | Three Dimensional |
| CG | Center of Gravity |
| CMA | Computational Modal Analysis |
| EMA | Experimental Modal Analysis |
| ESA | European Space Agency |
| FNF | Fundamental Natural Frequency |
| FRF | Frequency Response Function |
| GCS | Global Coordinate System |
| MSc. | Master of Science |
| NASA | National Aeronautics and Space Administration |

# CHAPTER 1

# INTRODUCTION

The current chapter will present an introduction to the current work, in terms of giving a context of its background, present the research questions and the primary objectives that the research effort strived to fulfil. It will also present the scope, limitations, and contributions of the research. As will be detailed in the subsequent chapters, the research effort was a mixture of computational analysis work, focusing on modal analyses as the first stage. The results from these modal analyses were validated by performing experimental work. Finally, computational dynamic loading analyses were performed, to explore the structural performance of the finalized design to expected loading cases.

## 1.1 Introduction to Satellite Systems

A satellite can be thought of as a combination of various subsystems, both mechanical and electronic in nature, known collectively as the *satellite bus*. These subsystems all work in unison towards a common goal, namely facilitating the operation of a *payload* system, which is launched into space to perform a specific mission. Payload missions include telecommunications, remote sensing of the earth and other celestial bodies, scientific missions, data gathering missions, plus types of missions.

Satellite bus subsystems operate in unison to support the operation of the payload. The following list gives the critical subsystems, upon which the satellite depends for operation:

- <u>The attitude dynamics and control subsystem:</u> controls the satellite's orientation while in orbit, such that the payload is always pointing its sensors towards the required geographical regions.
- <u>The power subsystem:</u> which deals with the various power generation and distribution requirements. This generated power is distributed to the other subsystems, plus the payload.
- <u>The communication subsystems:</u> two subsystems handle communications between the satellite and its controlling ground station. One subsystem works exclusively to send the payload sensor data to the ground station. The second subsystem handles the commands sent from the ground station to the satellite. These commands, related to the various bus and payload subsystems, activate or deactivate certain functions, as needed. It also sends subsystem operational data back to the ground station.
- <u>The thermal control subsystem:</u> which controls the thermal balance of the satellite's subsystems. Temperatures are increased or decreased to keep the subsystems within their required operating parameters. It

also handles the process of removing any unwanted thermal energy from the satellite, through ejecting it into space.

- The structure subsystem: The primary focus of the current work, as described below.

Among the satellite bus subsystems, the structural subsystem has a special importance. It performs two primary functions, towards ensuring that the mission will be achieved successfully. Its primary function is that it acts as the skeleton of the satellite. Namely, it acts as the mounting platform upon which all the other satellite subsystem components are mounted, including the payload components. An extension of this function is that its geometric shape is that of the satellite as a whole, and can take various forms: prismatic, cylindrical, polyhedral, spherical, etc.

The second primary function of the structural subsystem is to withstand the harsh dynamic loads that are imposed upon the satellite by the launcher vehicle, that transport it to its operational orbit. These loads occur during the launch phase, starting with the launcher leaving the earth's surface, passing through the earth's atmosphere, and finally injecting the satellite into its final operational orbit. Launch systems, such as the Falcon 9 from SpaceX [1] and the Electron from Rocket Labs [2], impose a relatively harsh dynamic loading environment on payloads during launch. These load environments include significant dynamic load levels that have the potential to lead to structural failure, if their effects are not taken into account in the structural design and analysis phases of any satellite development program. The structural subsystem must be able to withstand the various dynamic loads by developing deflections and stresses that do not reach the structure's material's yield point. If this point is reached by the material, permanent geometric deformations would occur, even when the loading is removed. If the structural design can achieve this requirement, the deflections and stresses will disappear after the launch phase is complete without the structure developing any permanent distortions. Any occurrence of these distortions would result in losing the carefully calibrated mounting positions of the payload's components, plus certain components within the bus's subsystems.

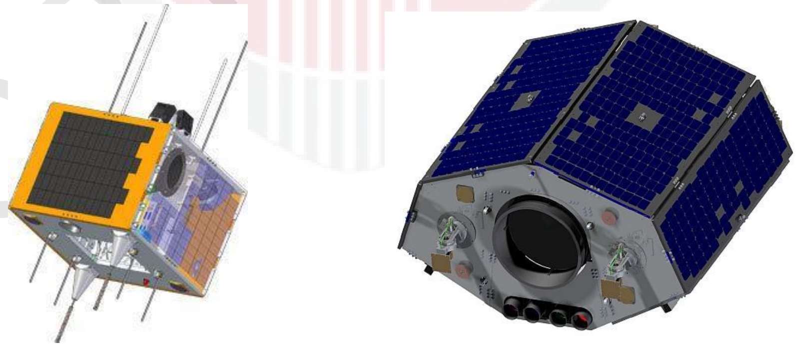
Satellites can be classified through several methods, based upon relevant parameters. However, the classification method most currently utilized is to classify by the satellite's total mass. The total mass is the mass of the structural components, plus the mass of any fuel on-board, if present, that would be utilized for in-orbit maneuvering. Table 1.1 presents the most widely accepted satellite classifications, based on their total masses [3].

**Table 1.1 : Satellite Classification Based on Total Mass**

| Classification | System Total Mass | Example |
|---|---|---|
| Femtosatellite | Less than 100 grams. | Pocketsat |
| Picosatellite | 0.1 – 1 kg. | 1U Cubesats |
| Nanosatellite | 1 kg – 10 kg. | 3U Cubesats |
| Microsatellite | 10 kg – 100 kg. | RASAT |
| Minisatellite | 100 kg – 1000 kg. | NigeriaSat-2 |
| Large Satellite | Larger than 1000 kg. | Intelsat |

The current trend in satellite design is to focus on the so-called “small satellite” category, with masses ranging from 1 kg (or less) up to 1000 kg (Sweeting [3], Kramer and Cracknell [4], Xue et al. [5]). Satellites in this mass range include enough volume to carry power-efficient payloads that can perform scientifically meaningful missions without requiring relatively large power budgets. Small satellites are mostly utilized for remote sensing and earth observation missions. Other mission examples include data collection from remotely installed ground sensors, scientific missions such as astronomical observations. Other types of missions that do not involve time-dependent constraints or high-power budget requirements can also be included.

Figure 1.1a shows a typical microsatellite, in this case the Turkish RASAT earth observation satellite [6], This system was launched into its 685 km altitude operational orbit during 2011 as a secondary payload onboard the Dnepr-1 Russian launch system and is still in service, and has a total mass of approximately 93 kg. Figure 1.1b shows a typical minisatellite, the NigeriaSat-2 [7], which is a disaster monitoring and earth observation system. It was launched into a 700 km altitude operational orbit during 2011 and is still in service, and has a total mass of approximately 300 kg.



(a) RASAT (Microsatellite) (b) NigeriaSat-2 (Minisatellite)

**Figure 1.1 : Typical Small Satellites**

## 1.2 Problem Statement

One of the critical design constraints when developing the structural design of a satellite is the reduction of its total mass [8]. This mass has a direct effect on the class of launcher to be utilized in launching the satellite to its operational orbit [9]. As a result of the choice of launcher, the costs of the launching process will increase as the class of the launcher increases. The current method of mass reduction generally applied in satellite structural design is to implement advanced materials, e.g., composite materials, in the design instead of standard metallic alloys. Even though these advanced materials offer reduced mass, and also good mechanical stiffness, they are very expensive to fabricate, plus require specialized knowledge in their design, analysis, and fabrication.

Thus, in this work, a lower-cost alternative option was proposed. Namely, standard aluminum alloy 6061 was utilized in the structural design, with the components fabricated through standard mechanical fabrication processes instead of implementing advanced materials. Patterns of perforations were implemented onto a number of structural components of the design. This had the aim of achieving a significant reduction in mass through direct material removal instead of utilizing advanced materials. These patterns were designed to be scalable, both in terms of their sizes and in terms of their coverage areas across the components being perforated by them. The current proposal strove to achieve reasonably good mechanical performance, in terms of withstanding the highly dynamic launch loads, without any permanent geometric distortions as a result of material yielding.

The proposed mass reduction method of the current work can be expanded upon in future works, towards being utilized in structural designs implementing advanced materials. It was also envisioned that the proposed mass reduction method could potentially be utilized with additive manufacturing processes, e.g., three-dimensional printing. The proposed method will remove additional mass from such structural designs, beyond that achievable through utilizing these materials or fabrication processes alone.

## 1.3 Research Aim and Objectives

The research effort aimed to develop and implement a new method to reduce the mass of the structure of a small satellite in the microsatellite mass classification range, as given previously. The novelty of the work was to introduce an alternate method of mass reduction, other than utilizing space qualified composite materials. This was towards drastically reducing the overall cost of developing such a structure, since the proposed method utilized direct material removal from structural components. The method would implement low-cost standard machining technologies, instead of the high-cost specialized design, analysis, and fabrication methods that are usually adopted by microsatellite structures.

In order to accomplish this aim, the current work strived to achieve the following objectives, in chronological order:

1. Adopt the baseline design of the structural subsystem, developed in the MSc. work, for a microsatellite that includes non-perforated components. In parallel, a computational modal analysis methodology was to be developed and implemented. This methodology was to be validated through experimental modal analysis procedures.
2. Construct a design space consisting of a set of parametrically defined geometric patterns, arranged into a number of geometric variations. Subsequently, computational modal analysis procedures were to be performed on the design space cases, in addition to the baseline case. The case with the closest fundamental natural frequency, relative to the baseline case value, would be selected as the best perforated alternative.
3. Revise and modify the selected perforated design such that its fundamental natural frequency matches that computed for the baseline case. This would be through implementing computational modal analysis in an iterative process.
4. Investigate the finalized perforation case's structural performance, through performing dynamic analyses utilizing the finalized design. This would be achieved by imposing the same nominal dynamic launch loads utilized for the baseline case. The results of these analyses would be the final indication that the proposed perforation process would yield a mass reduced design that was viable, and suitable for future development and implementation.

## 1.4 Research Questions

Utilizing the 5W+1H method for project planning and question formulation, as implemented by Knop and Mielczarek [10], Hamborg et al [11], and Almeida et al [12], the current work's problem statement can be posed as follows:

1. <u>What:</u> What is the proposed method introducing, in terms of a novel implementation of a previously utilized method of mass reduction in other engineering fields? (Objective 1)
2. <u>Why:</u> Why is the proposed method of importance for satellite structural designers? (Objective 1)
3. <u>When:</u> At what stage in a satellite structure's design process can the proposed method be implemented? Can it be introduced during the initial design stages? Can it be implemented onto an existing design? (Objective 1)
4. <u>Where:</u> Where can this proposed method be implemented, in terms of a satellite's structural design? Can the proposed method be

implemented on any structural component, or are there prerequisite design considerations that must be met? (Objectives 2 and 3)

5. Who: Can the method be easily implemented by structural system designers in a timely and straightforward way? (Objectives 2 and 3)

6. How: How can the steps for implementing the proposed mass reduction method be characterized, including proving its merit such that it can be implemented in future structural system designs? (Objective 4)

## 1.5 Scope and Limitations of the Current Work

The scope of the current work was to consider the structural subsystem of a conceptual microsatellite that was previously designed by the researcher in his Master of Science research work, taking the design in its unperforated form. The aim of the work was to strive to reduce its mass to a significant degree by introducing parametrically defined geometric patterns to three of its components as metal perforation patterns. The idea of implementing the perforation patterns was proposed as an alternative to implementing composite materials, which would have been much more costly to implement. The parametrically defined geometric patterns were defined as a design space consisting of four geometric shapes, namely diamonds, hexagons, squares, and triangles. Each of these four shapes were modified by changing their aspect ratios and scale factors, generating a total of twenty variations.

Each of the design study variations were implemented onto the baseline structure, hence generating twenty variations of the structural assembly, plus the baseline case. To select the best variation, relative to the baseline, modal analysis was utilized in the current work as a design tool to differentiate between the perforated cases. Each case's fundamental natural frequency was compared to that of the baseline case, and the selected case was the one with the least difference in value.

The aforementioned modal analysis processes implemented in the current work were all based upon computational modal analysis procedures, employing the finite element method. However, before the results computed through these procedures could be endorsed, it was necessary to validate them. This was achieved by comparing modal results computed by the computational modal analysis procedures on scaled down models of a single structural component with results acquired from fabricated models of the same models. These last set of results were acquired through experimental modal analysis procedures. Both the baseline unperforated form and the perforated form of this component, employing the four geometric patterns mentioned above were considered. A good correlation between the two result sets would validate the computational modal analysis procedures, which could then be endorsed with a reasonable level of confidence. Computational modal analysis was again employed to refine the modal results of the aforementioned selected perforation case. This was done towards increasing its fundamental natural frequency to match that of the baseline case. An iterative process that varied the number of repetitions of the perforation patterns implemented on the components was employed. This resulted in the finalized, definitive, perforated design.

The final step in the research effort of the current work was to impose three of the nominal dynamic loads that would be expected to be applied to the structure while undergoing launch to the satellite's operational orbit. The structure's structural responses were computed through computational dynamic analyses, for both the baseline and finalized perforated cases, and the main parameter was the yield margin of safety computed for each case.

In terms of the limitations of the current work, no consideration was made to include any satellite subsystem components in any of its computational or experimental analyses. This was because the current work was focused only on the developing the perforation patterns for implementation onto structural subsystem itself, leaving such investigations to future works. Another limitation was forced upon the research team, regarding the experimental modal analyses. It can be seen in Chapters 3 and 4 that only one component was submitted to analysis, after fabrication, namely single central box plates. This limitation came from the fact that an insufficient number of vibration sensing transducers were available to the candidate. This resulted in distorted modal results when structural subassemblies were tested. This limitation can be overcome in future works, when a larger number of transducers can be made available to capture the modal results in a coherent fashion.

## 1.6 Contribution of the Current Work

The current work introduces a new method of structural mass reduction to astronautic structural design and engineering. Its main focus is on achieving significant reductions in total satellite mass while keeping the budgetary requirements of the structural design at a much lower level than the current practice of introducing advanced structural materials. Savings of at least a tenth of the required cost were projected. These were relative to implementing these advanced structural materials, in terms of design, analysis, and fabrication requirements (e.g., specialized design and analysis software, material procurement costs, etc.). These savings were thereby expected to achieve significant monetary savings in terms of the overall program costs. The proposed mass reduction method also involves significantly reduced structural fabrication costs, relative to fabrication costs for components implementing these advanced structural materials, hence introducing additional monetary savings.

## 1.7 Thesis Layout

**Chapter one** of the current thesis presents an introduction to the work, in addition to presenting its primary research objectives, research scope, main contributions, and a description of its chapters.

**Chapter Two** presents a review of past works that the current work built upon and expanded, identified the gap that the current work strived to fill. This included a description of the baseline structural design as developed in the original MSc. work. Also, it presented mathematical descriptions of the main parameters that were hence computed or acquired during the course of the research efforts, towards building the result sets through which the primary objectives were achieved.

**Chapter Three** introduces the research methodologies that were developed and implemented towards achieving the work's primary objectives. These included the basic premise of designing the work's geometric perforation patterns, and also descriptions of both the computational and experimental analysis methodologies that produced the result sets. It also describes the dynamic launch loads that we imposed upon the finalized structural design, in terms of specific numerical values.

**Chapter Four** presents the numerical result sets either computed or acquired as a result of implementing the computational and experimental methodologies described in Chapter three. This chapter also includes detailed discussions of the numerical results, and their impact on the overall effort to fulfill the research work's primary objectives.

**Chapter Five** presents the conclusions of the current work, in addition to the suggestions that can be utilized by future researchers to carry forward the current work's research.

**Appendices A, B, and C** are included in the current work. Appendix A gives a summary of the original research work accomplished by the candidate during his MSc. work. This work resulted in a design of a structural subsystem for a conceptual microsatellite. The original work led to the design of a set of perforation patterns based upon the Isogrid system, and this Appendix gives these designs, presenting them as baselines for the perforation patterns developed and presented in the current work. Appendix B gives the mathematical details of the current work's designed perforation patterns, in terms of the geometric equations that were developed and utilized in the current work. Appendix C gives the dimensioned engineering drawings of the structural design's components, both baseline and perforated.

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