UNIVERSITI PUTRA MALAYSIA

MATHEMATICAL MODELLING OF FINENESS RATIO EFFECTS ON AERODYNAMIC CHARACTERISTICS OF AN AIRSHIP DESIGN USING COMPUTATIONAL ANALYSIS

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By

JAFIRDAUS BIN JALASABRI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, In Fulfilment of the Requirements for the Degree of Master of Science.

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Airships used to be the primary passengers' air transportation means before the jet aircraft took over their role. This happened due to the operational safety concerns after several fatal accidents involving the airships. In recent times however, modern airship designs have been improved and their operational efficiency is said to be better than jet aircraft in many areas. This leads to the idea that airships can be used to revolutionize the current mass public transportation means that are facing several issues of low operational effectiveness and worsened traffic congestion. Though recent airship designs have many advantages, they are not developed for use as a mass public transportation vehicle. To accommodate more passengers onboard, these airship designs might be required to be sized or scaled up and this subsequently affects their aerodynamic performance due to their modified external shape. Therefore, in developing successful airship designs for public transport purposes, it is important for designers to fully understand the effect of the design on the performance of the airship. The external shape design changes can be aptly captured by design fineness ratio parameter of the airship, which is defined as the ratio of the airship's length to its maximum width. Nonetheless, there is a general lack of aerodynamic models that are established for airship design purposes and this is the main identified gap to be addressed in this study. Specifically, the aim of this research work is to establish the effects of design fineness ratio of an airship towards its aerodynamic performance.

The Atlant-100 airship is chosen as the reference design model for this study. An approximate computer-aided design (CAD) model of the Atlant-100 airship is constructed using CATIA software and it is applied in computational fluid dynamics (CFD) simulation analysis using StarCCM+ software. In total, 36 simulation runs are executed with different combinations of values for fineness ratio, altitude and velocity. The obtained CFD simulation results are then statistically analyzed using Minitab software to evaluate the significance of the design fineness ratio effects and formulate the mathematical model between the design fineness ratio and the aerodynamic lift and

drag forces of the airship design. From the obtained simulation results, it has been found that smaller fineness ratio for Atlant-100 model will correspond to higher aerodynamic lift and drag forces. As in the case simulated in this study, the smallest fineness ratio of 0.93 has been shown to correspond to the highest value of generated lift coefficient while having similar comparable value of generated drag coefficient with the other fineness ratios. This highlights that a smaller fineness ratio of the airship design is more suitable for the mass public use. In addition, from the statistical analysis done, the effects of the fineness ratio to the generated aerodynamic lift and drag forces can be said to be significant. The constructed mathematical models to capture these effects have also been validated with a few goodness-of-fit tests. For the regression model of fineness ratio impact on the lift coefficient, it has R^2 value of 0.941. When its predictive accuracy is tested with some simulated random cases, the maximum error obtained is only 6%. On the other hand, for the regression model of the fineness ratio impact on drag coefficient, the R^2 value is 0.962 and the maximum predictive error from the simulation random cases test is only 9%.

All in all, it can be concluded that the constructed regression models have a good predictive capability to predict the impact of the design fineness ratio on the aerodynamic performance of the airship. With the results from this study, designers can make use of the regression models to predict the right fineness ratio of the airship design for a given mission profile based on expected aerodynamic performance, or vice versa.

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

PERMODELAN MATEMATIK BAGI KESAN NISBAH KEHALUSAN KE ATAS CIRI AERODINAMIK SEBUAH REKABENTUK KAPAL UDARA MENGGUNAKAN ANALISIS KOMPUTASI

Oleh

JAFIRDAUS BIN JALASABRI

Mac 2018

Pengerusi : Fairuz Izzuddin Romli, PhD
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Kapal udara pernah menjadi cara utama untuk pengangkutan udara sebelum pesawat jet mengambil alih peranannya. Ini berlaku kerana kebimbangan terhadap keselamatan operasinya selepas berlakunya beberapa kemalangan maut melibatkan kapal udara. Pada ketika ini walaubagaimanapun, rekabentuk moden kapal udara telah ditambah baik dan tahap kecekapan operasinya dikatakan lebih baik di dalam pelbagai aspek jika dibandingkan dengan pesawat jet. Ini membawa kepada idea yang kapal udara dapat digunakan untuk merevolusikan pengangkutan awam sekarang yang sedang menghadapi pelbagai isu berkaitan keberkesanan operasi yang rendah serta kesesakan trafik yang kian meningkat. Walaupun rekabentuk kapal udara terkini ini mempunyai pelbagai kelebihan, namun ia tidak dibangunkan sebagai sebuah kenderaan pengangkutan awam. Untuk menampung lebih ramai penumpang, rekabentuk kapal udara ini berkemungkinan perlu disaiz atau diskala besar dan ini akan memberi kesan kepada prestasi aerodinamik disebabkan oleh perubahan bentuk luarannya. Oleh itu, bagi membangunkan rekabentuk kapal udara sebagai pengangkutan awam, adalah penting bagi pereka bentuk untuk memahami secara keseluruhannya tentang kesan rekabentuk tersebut terhadap prestasi kapal udara. Perubahan bentuk luaran rekabentuk boleh diambilkira melalui parameter nisbah kehalusan, iaitu nisbah panjang bagi kapal udara itu kepada lebar maksimumnya. Namun, terdapat kekurangan model aerodinamik yang dibangun untuk tujuan reka bentuk kapal udara dan ini ialah jurang utama yang dikenalpasti dalam kajian ini. Secara spesifiknya, sasaran kerja bagi penyelidikan ini adalah untuk menentukan kesan nisbah kehalusan rekabentuk sebuah kapal udara terhadap prestasi aerodinamiknya.

Kapal udara Atlant-100 dipilih sebagai model rekabentuk rujukan bagi kajian ini. Satu model rekabentuk hampiran berbantu komputer (CAD) bagi kapal udara Atlant-100 telah dihasilkan menggunakan perisian CATIA dan ia digunakan dalam analisis simulasi komputasi dinamik bendalir (CFD) menggunakan perisian StarCCM+. Secara keseluruhannya, 36 kes simulasi telah dijalankan dengan pelbagai kombinasi berbeza bagi nilai nisbah kehalusan, altitud dan halaju. Keputusan simulasi CFD yang diperolehi

kemudiannya dianalisa secara statistikal menggunakan perisian Minitab bagi menilai tahap kepentingan kesan nisbah kehalusan rekabentuk serta membangun model matematik antara nisbah kehalusan rekabentuk dengan daya angkat dan geseran aerodinamik bagi rekabentuk kapal udara. Dari keputusan simulasi yang diperolehi, didapati nisbah kehalusan yang rendah bagi model Atlant-100 adalah berpadanan dengan nilai daya angkat dan geseran aerodinamik yang lebih tinggi. Dari kes simulasi yang dijalankan dalam kajian ini, nisbah kehalusan yang terendah iaitu 0.93 telah menunjukkan nilai yang tertinggi bagi daya angkat dan nilai daya geseran yang hampir setara dengan nisbah kehalusan yang lain. Ini menunjukkan bahawa nisbah kehalusan rekabentuk kapal udara yang rendah lebih sesuai bagi kegunaan pengangkutan awam. Selain itu, daripada analisis statistik yang dilakukan, kesan nisbah kehalusan atas daya angkat dan geseran aerodinamik adalah penting. Model matematik yang dihasilkan bagi merangkumi kesan ini telah disahkan melalui beberapa ujian ujian kebagusuaian. Bagi model regresi kesan nisbah kehalusan terhadap pekali daya angkat, nilai R^2 model ini adalah 0.941. Apabila tahap kejituan ramalannya diuji dengan beberapa simulasi kes rawak, ralat maksima yang telah diperolehi adalah hanya 6%. Sementara itu, bagi model regresi kesan nisbah kehalusan terhadap pekali daya geseran, nilai R^2 adalah 0.962 dan ralat maksima kejituan ramalannya melalui simulasi kes rawak adalah hanya 9%.

Secara keseluruhannya, kedua model regresi ini boleh disimpulkan sebagai mempunyai tahap kejituan ramalan yang baik untuk kesan nisbah kehalusan rekabentuk ke atas prestasi aerodinamik kapal udara. Dengan keputusan yang telah diperolehi daripada kajian ini, para pereka bentuk dapat menggunakan model regresi ini untuk meramalkan nisbah kehalusan rekabentuk kapal udara yang sesuai bagi profil misi yang diberi berdasarkan kepada anggaran prestasi aerodinamik yang diingini, atau sebaliknya.

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Lastly, I wish to thank all people who I have encountered and also worked with during this research study for making this a reality, and to whom I am forever and truly grateful.

I certify that a Thesis Examination Committee has met on 30 March 2018 to conduct the final examination of Jafirdaus bin Jalasabri on his thesis entitled "**MATHEMATICAL MODELLING OF FINENESS RATIO EFFECTS ON AERODYNAMIC CHARACTERISTICS OF AN AIRSHIP DESIGN USING COMPUTATIONAL ANALYSIS"** in accordance with the Universities and University Colleges Act 1971 and the Constitution of Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the degree of Master of Science

Members of the Thesis Examination Committee were as follows:

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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 Master of Science. The members of the Supervisory Committee were as follows:

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School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

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- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
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Signature: ______________________________
Name of Chairman of Supervisory Committee: Dr. Fairuz Izzuddin Romli

Signature: ______________________________
Name of member of Supervisory Committee: Dr. Mohammad Yazdi Harmi

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
ASEAN	Association of Southeast Asian Nations
CAD	Computational Aided Design
CATIA	Computer Aided Three-Dimensional Interactive Application
CFD	Computational Fluid Dynamic
COSH	Control of Static Heaviness
DoE	Design of Experiments
ENIAC	Electronic Numerical Integrator and Computer
FDM	Finite Difference Method
FEM	Finite Element Method
FR	Fineness Ratio
FVM	Finite Volume Method
HAV	Hybrid Air Vehicles
HTA	Heavier-Than-Air
LRT	Light Rail Transit
LTA	Lighter-Than-Air
MAAT	Multibody Advanced Airship for Transportation
PDE	Partial Differential Equation
RANS	Reynolds-Averaged Navier Stoke
SIM-PLE	Semi-Implicit Method for Pressure Linked Equation
SST	Shear Stress Transport
STOL	Short Take-off and Landing
VTOL	Vertical Take-off and Landing

CHAPTER 1

INTRODUCTION

1.1 Research Overview

Transportation has become a necessity in life nowadays. In urban areas, public transportation is essential for the growth of social and economics of the society. However, as one of the rapidly urbanized countries in ASEAN region, Malaysia is facing problems with traffic congestion that has also been affecting the quality and efficiency of local transportation. This situation is contributed to the high number of vehicles on the road. For example, in the Klang Valley area alone where 4.8 million people live, about 48% of them are car owners (Ariffin and Zahari, 2013). Because of the high traffic volume, road congestion problems become more severe and leads to higher wasted travelling time and cost, fuel consumption, air and noise pollution, and also accident and fatality rates (Kasipillai and Chan, 2008).

Public transport services have been offered to alleviate this situation, apart from providing the transportation access to the society at large, especially for people without own private vehicles. Nonetheless, as evident from current situation, the effectiveness of public transport services to solve traffic congestion problems in the urban areas has been rather low. This is mainly because of several factors that have hindered the full use of public transportation options, particularly in encouraging modal shift from private car to public transport users. Several revolutionary ideas have been proposed to improve and cope with worsening traffic congestion problems by increasing the quality of public transportation services. It is believed that a new alternative public transport means that can aptly utilize the third dimension of the transportation network, which is the airspace above, can help to further improve the situation. This is closely similar to the concept of a personal air vehicle that is proposed for private vehicle (Romli and Rashid, 2015). In this case, the concept can be conceived as some sorts of a public "flying bus" and airships have been studied to become the transport vehicle. One of the prominent development projects for this revolutionary public transport concept is Multibody Advanced Airship for Transportation (MAAT) that is supported by the European Union. In this particular project, a novel approach in developing a feeder-cruiser system of airship operation is researched for the transportation of people and goods (Ilieva *et al*, 2014).

When the urban "flying bus" idea is proposed, the airships seem to be the most suitable means for such transportation concept. Airship is no stranger to the public transportation field, having served as the commercial air transportation means since early 1930s. However, a series of fatal incidents during operation has hindered its design and development progress. Of note is the famous Hindenburg incident, where the transportation airship caught fire and was destroyed while trying to dock, killing a total of 36 people and effectively ending the era of airship in commercial air transportation field. Since then, the airships' usage has been limited to mainly tourism and advertising purposes (Stockbridge *et al*, 2012). However, with new technology advancements that have led to the much safer airship operation, its recent comeback has been fuelled by market interests and demands (Prentice *et al*, 2005). There are several recent airship researches and development projects discussed in the literatures (Stockbridge *et al*, 2012; Battipede *et al*, 2013). With these developments and interests on use of airships as transportation means, it is not impossible that they could be operated to alleviate traffic congestion within urban cities as alternative mass public transportation option (Aminian and Romli, 2017). Figure 1.1 illustrates an example vision of having the airships operating as public transportation means in urban cities.

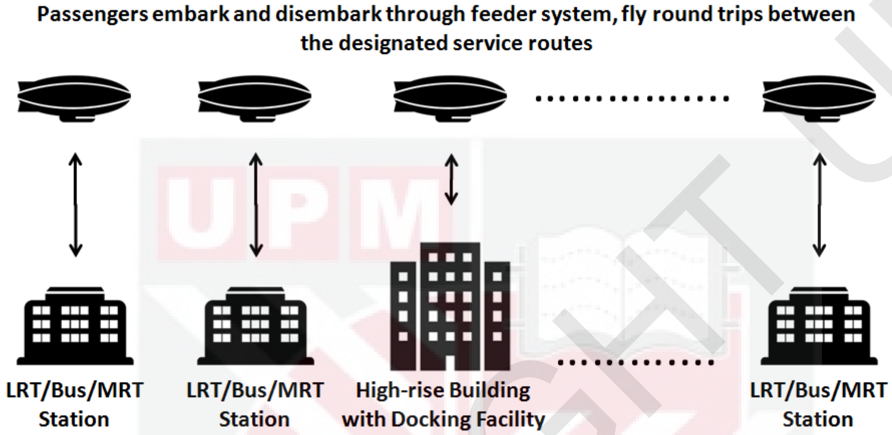

Figure 1.1: Anticipated Mission Profile of Public Transport Airships (Aminian and Romli, 2017)

Airships have some advantages that make them suitable for public transportation use. Among others, these include the reduction of fuel dependency and lower air pollution. The airships also have a great advantage of being able to operate without requiring runway facility for take-off and landing, bypassing problems of airport congestion or road traffic. Figure 1.2 shows the comparison of fuel consumption and speed between airships and several other transportation means. In addition, Table 1.1 tabulates the comparison of a few operational characteristics of airships against those of the other transportation modes, which further supports the potential benefits of proposed use of airship for public transportation.

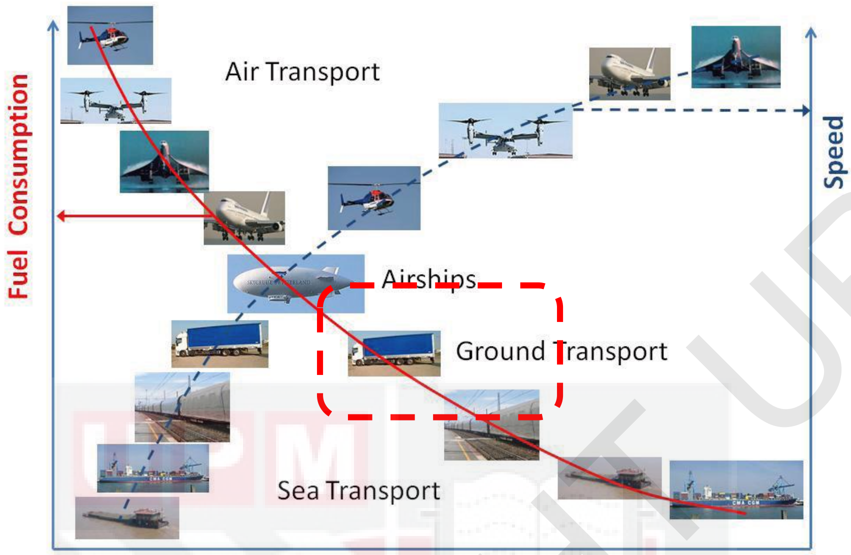

Figure 1.2: Airship Fuel Consumption and Speed Versus Conventional Transport Systems
(Stockbridge, 2012)

Table 1.1: Operational Comparison of Airships Against Other Transport Modes (Schafer and Waltz, 2014)

Operational Characteristics	Airship versus Maritime	Airship versus Highway	Airship versus Railway	Airship versus Aerial
Speed	Much faster	Faster	Much faster	Much slower
Load Capacity	Less capacity	Much more capacity	Less capacity	Increased capacity
Load Adaptability	Much more flexible	Less flexible	Much more flexible	More flexible
Transportation Cost	Much more expensive	More expensive	Much more expensive	Much more economical

1.2 Research Background

Designing an airship highly depends on aerodynamic theory than the design of aircraft. This is because its size is much bigger, it is more expensive and its structure can be hardly modified after its complete construction (Munk, 1936). Hence, trial and error design method is rather unsuitable for the development of an airship. This puts a big emphasis on the understanding of its aerodynamic performance and the ways to effectively predict this performance during the design process. Unfortunately, there is a general lack of studies that have been done on the aerodynamics of an airship, especially the current modern hybrid airship designs (Andan *et al*, 2012). Some of recent computational and experimental studies done on aerodynamics of an airship include Andan *et al* (2012), Wang *et al* (2010) and Sun *et al* (2018). However, these studies are made for specific airship design points and do not include any parametric study that can help to show the trend of the aerodynamic characteristics of the airship beyond its current design. It is highly useful to have an insight on changes in the airship's aerodynamic performance as its external shape design is modified during the early design stages. This is especially true if the current airships that have been developed for different purposes such as surveillance, tourism and advertising are to be modified for use as public transportation means.

The modification in external shape can be captured by using design fineness ratio parameter, which is defined as the ratio of the length of the body against its maximum width. In aerospace, the fineness ratio is used to describe the overall shape of a streamlined body and it is one of the common design parameters included in aerodynamics and also weights and sizing analyses (Unal *et al*, 1998). The impact of fineness ratio parameter on the aerodynamic characteristics of a body has been demonstrated in several studies which include Sahai *et al* (2014), Kruger *et al* (2016) and also Nicolosi *et al* (2016). All these studies have shown that different fineness ratio will correspond to different aerodynamic characteristics of the body. Essentially, this can be taken to indicate that fineness ratio is an effective parameter to be used to capture the modification of the external design shape of the body and the subsequent effects that it has on the aerodynamic performance of the body.

An example study on the effect of design fineness ratio of an airship on its drag performance is shown in Figure 1.3. In airship design, the pressure-difference resistance is typically lower as the airship has a much slender and long design. As can be observed in Figure 1.3, the increase in fineness ratio will lead to the increase in surface area and skin friction around the airship's body area.

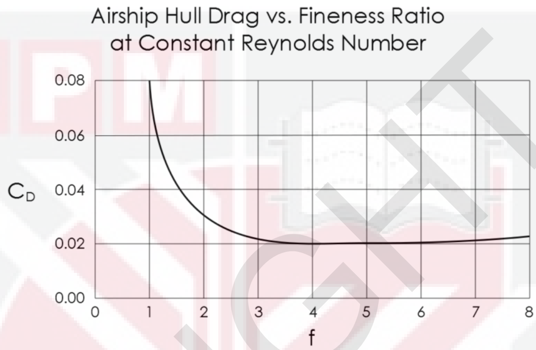

Figure 1.3: Effect of Fineness Ratio On Variation Hulls
(FAA, 1941)

All in all, in order to do a parametric study on the possible effects of changing the airship design to its aerodynamic performance, it can be taken that the fineness ratio is a good design variable to capture the essences of the impacts.

1.3 Problem Statement

It has already been argued and discussed in the previous sections on the suitability of having airships as an alternative public transport means. In developing a successful airship design for public transport purposes, it is important for the designers to fully understand the effect of the design on aerodynamic performance of the airship. The aerodynamic model of the airship could be markedly different from traditional aircraft designs, which many of the latter models have been well-established using historical data. To date, there are only few available publications that address aerodynamic modelling of airships in the public domain (Mueller et al, 2004). Airship relies on buoyancy to generate its static lift and the shape of airship is the main contributor to high drag value (Shields, 2010). In addition, the aerodynamic study also plays an important role in optimizing weight and design of the airship. Since many of the existing airship designs are not meant for mass public transportation, they probably have to be sized or scaled up to suit with their new purpose. This is believed to have a large impact on their aerodynamic performance but with lack of established model that capture this relationship, it is hard to roughly determine the scale of the impact.

In early design process, the designer can make better design decision if more information about the design parameters and the effects on the overall performance is available. In this case, a good predictive model on how the changes in the airship design can affect its overall aerodynamic performance will be very beneficial to the designers. As established in the previous section, design fineness ratio has been used and is a good design parameter to be applied to capture the link between the modification of the external body shape and its effects on the aerodynamic characteristics. It is therefore the main aim of this research study to explore and establish the mathematical models that appropriately capture the resultant impact trend of airship design on its aerodynamic performance through the use of its fineness ratio parameter as the main design variable.

1.4 Research Objectives and Hypothesis

Up until this point, the motivation or driving need for this research work has been sufficiently established. This research is narrowed down to the establishment of the mathematical models that capture the effects of the design fineness ratio on the lift and drag forces acting on the airship to be designed as an alternative public transport means. In conjunction with this, the purpose statement for this thesis work is to develop the mathematical models of design fineness ratio effects on aerodynamic characteristics of an airship.
In corroboration with the above work intent, the following research objectives are set up as listed below. These research objectives are essential to support the achievement of the aim of this study.

Research Objective 1: To study the effects of fineness ratio on the aerodynamic characteristics of an airship design

Research Objective 2: To establish the mathematical models of the fineness ratio effects on the airship aerodynamic characteristics

Research Objective 3: To validate the mathematical models of the fineness ratio effects on the airship's aerodynamic performance

In order to address these research objectives, the following research questions have been formulated. These questions will subsequently become the foundation of literature review study presented in this following chapter.

Research Question 1: What is the most suitable type of airship design for use in mass public transportation?

Research Question 2: How to simulate aerodynamic performance effects of an airship model due to varying fineness ratio?

Research Question 3: How to develop the mathematical model in relating the airship's aerodynamic performance parameters to its design fineness ratio?

The goal of the first research question is to identify and also select the most suitable reference airship design for public transportation purposes. This airship design will become the test model for the simulation study to observe possible effect of the fineness ratio on its aerodynamic performance. The methods and tools to be applied in the simulation study are identified through the second research question. Last but not least, the third research question is formulated to identify mathematical modelling method that can be applied with the obtained simulation results for development of the relationship model.

It is strongly believed that aerodynamic characteristics of the airship will be affected by the changes in its design fineness ratio and thus this is taken as the research hypothesis for this study. In order to prove this hypothesis, aerodynamic performance parameters of the airship, namely lift and drag coefficients, should be shown to be affected by the changing value of the design fineness ratio.

1.5 Research Scope

A complete modelling of the underlying relationships between the design parameters of the airship and its aerodynamic performance is a rather big research area. This is because many parameters can be included into the model. In this study, some limitations are applied to the problem scope to better refine its focus and align it with the expected workload of a Master's degree.

Firstly, this study only considers the design fineness ratio as the representative parameter for the airship design or shape. The ratio, which is defined as the length of the airship body over its maximum width, is commonly used to describe overall shape of streamlined body in the aerospace engineering field. On the other hand, for the aerodynamic performance parameters, the ones that will be focused in this study are the generated lift and drag coefficients. In addition, altitude and velocity parameters are also added into the analysis to represent the operational mission factors.

Secondly, the exploration and modelling of the relationship will be done with simulation analysis. This means that there is no prototype development or experimental testing involved. The simulation set-up will undergo the typical verification stage to ensure that its results are comparably accurate.

Thirdly, the computational analysis will use basic turbulent models, specific air condition and mesh combination due to lack of computer power capabilities to analyse more advanced computational analysis interactions. This will result only the required area for analysis used in detail refinement to reduce number of cells and computing times. Additionally, only specific Reynolds numbers have been selected for incompressible turbulent airflow at low air speeds based on certain air conditions between the velocities of 100 km/h to 250 km/h and altitudes of 1500 m to 2500 m. Most of the CFD software are able to provide high level aerodynamic insight but it still cannot capture the accurate full detail of the complex turbulent airflow usually due to computing capabilities.

Last but not least, the modelling will involve one reference airship design that will be selected among existing ones that are available today. The selection will be made based on several characteristics that are taken to be vital for suitability of public transport purposes. Therefore, since the study is narrowed down to one specific airship design, its results might not be directly applicable to other designs even though the trend may be similar.

1.6 Thesis Organization

Overall structure for this thesis documentation is as follows. This first chapter is meant to build the case for relevance of this research study by explaining its motivation. In addition, the study scope has been outlined by defining its limitations. Chapter 2 reports upon the literature review study that has been done to identify the available information and state-of-the-art technologies to assist in the study. The literature review is conducted according to research questions, which are tailored to research objectives. In the following Chapter 3, the planned research methodology to test this research hypothesis is discussed. Chapter 4 presents the details of research work done in this study. Lastly, this thesis concludes with Chapter 5 that contains the assessment on the achievement of the research objectives and the overall discussion on this research work and suggested future work.

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