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STABILITY AND CONTROL OF HYBRID AIRSHIPS: A NEW CONCEPT

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AVISO

A presente dissertação foi realizada no âmbito de um projeto de investigação desenvolvido em colaboração entre o Instituto Superior Técnico e a Universidade da Beira Interior e designado genericamente por URBLOG - Dirigível para Logística Urbana. Este projeto produziu novos conceitos aplicáveis a dirigíveis, os quais foram submetidos a processo de proteção de invenção através de um pedido de registo de patente. A equipa de inventores é constituída pelos seguintes elementos:

- *Rosário Macário, Instituto Superior Técnico;*
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As partes da presente dissertação relevantes para efeitos do processo de proteção de invenção estão devidamente assinaladas através de chamadas de pé de página. As demais partes são da autoria do candidato, as quais foram discutidas e trabalhadas com os orientadores e o grupo de investigadores e inventores supracitados. Assim, o candidato não poderá posteriormente reclamar individualmente a autoria de qualquer das partes.

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(*Diego Núñez González*)

Dedicatory

I want to dedicate this work to my family and many friends. A special feeling of gratitude to my loving parents, Enrique and Amparo, whose words of encouragement and support made me believe in me every day. To my sister Vane and my little nephew Víctor, this is for you too.

I also dedicate this work to my friend Ángel, for his support over all these years, and each and every one of my friends.

“Lo importante no es llegar, sino el camino en sí”.

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Abstract

Nowadays, airships are generating a growing interest. The development of new technologies has allowed hybrid airships to become a reality, leading to a significant number of new research projects. In this way, numerous lines of research are opened in all areas of airship designs and, especially, this will allow the development of stability and control systems that are truly efficient.

To overcome this limitation in the stability and control there are numerous possible solutions for hybrid airships. This thesis' objective is to analyze the feasibility and performance of a new concept of stability and control system. This system is a combination of two elements: a distribution of six control surfaces and a set of four variable pitch rotors.

For that, four different prototypes were built. Two of them are a scale model of the airship aimed to test the stability and control of all surfaces. The third one is a quad rotor to analyze the behavior of a variable pitch solution. Finally, the last prototype is a scale model again, but this time aimed to test the performance of a quad rotor airship with fixed pitch control.

The results from the different tests showed this concept is a promising way to stabilize and control a hybrid airship. Tests of the first prototype validated a new mode of control which solves different problems related to the stability and control. The results from the tests of prototype 1.5 confirmed that a six surfaces configuration allows full control for different types of performance, being necessary to continue investigating this concept as well as its implementation along with a system of rotors. Prototype 2 results showed that a variable pitch rotor solution for a quad rotor provides an effective and feasible control, among other advantages. The results from prototype 2.5 showed that because the airship model does not have an internal or external structure, it has vibration problems at high rotor power settings. In addition, the airship was uncontrollable when utilizing a system of fixed pitch rotors, so it is necessary to study the implementation of the variable pitch ones.

Finally, one can conclude that the combination of a system of six control surfaces with a system of four rotors with variable pitch is a promising way to stabilize and control a hybrid airship.

Keywords: Hybrid Airship, Stability and Control System, Surfaces System, Variable Pitch

Resumo

Hoje em dia, os dirigíveis estão gerando um crescente interesse. O desenvolvimento de novas tecnologias tem permitido aos dirigíveis híbridos tornar-se uma realidade, multiplicando o número de investigações sobre eles. Desta forma, inúmeras linhas de investigação são abertas em todas as áreas de desenho dos dirigíveis e, especialmente, isso permitirá que o desenvolvimento de sistemas de controlo e de estabilidade que são verdadeiramente eficientes.

Para superar essa limitação na estabilidade e no controlo existem numerosas soluções possíveis para os dirigíveis híbridos. O objetivo desta tese é analisar a viabilidade e o desempenho dum novo conceito de sistema de estabilidade e controlo. Este sistema é uma combinação de dois elementos: uma distribuição de seis superfícies de controlo e um conjunto de quatro rotores de passo variável.

Para isso, foram construídos quatro protótipos diferentes. Dois deles são um modelo em escala do dirigível com o objetivo de testar a estabilidade e controlo de todas as superfícies. O terceiro é um quad rotor para analisar o comportamento de uma solução de passo variável. Finalmente, o último protótipo é novamente um modelo em escala, mas desta vez tem como objetivo testar o desempenho de um dirigível quad-rotor com controlo de passo fixo.

Os resultados dos diferentes ensaios mostram que este conceito é um caminho promissor para estabilizar e controlar um dirigível híbrido. Os testes do primeiro protótipo validaram um novo modo de controlo que resolve diversos problemas relacionados com a estabilidade e o controlo. Os resultados dos ensaios do segundo protótipo confirmaram que uma configuração de seis superfícies de controlo permite um controlo total para diferentes atuações, sendo necessário continuar a investigação deste conceito e a sua implementação em conjunto com um sistema de rotores. Os resultados do protótipo 2 mostraram que uma solução de passo variável proporcionará um controlo eficiente e fiável para um quad rotor, entre outras vantagens. Os resultados do protótipo 2.5 mostraram que ao não ter uma estrutura interna ou externa, o dirigível têm problemas de vibrações para grandes potências nos rotores. Além disso, o dirigível foi incontrolável quando se utilizou um sistema de rotores de passo fixo, por isso é necessário estudar a implementação de passo um sistema de passo variável.

Finalmente, pode-se concluir que a combinação de um sistema de seis superfícies de controlo com um sistema de quatro rotores com passo variável é um caminho promissor para estabilizar e controlar um dirigível híbrido.

Palavras-chave: Dirigível Híbrido, Sistema de Estabilidade e Controlo, Sistema de Superfícies, Passo variável

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1. Introduction

1.1. Motivation

Despite airships have been used for many years [1], their implementation has not been as strong as one might expect and their uses are mainly limited to surveillance, leisure and advertisement.

Even so, right now there is a growing interest regarding their use into new areas due to the implementation of new technologies. Thus, the utilization of composite materials, vectoring motors or computer assisted design among others represent a significant advance pathway.

The unification of these developments leads to a new type of airship, the Hybrid Airship. This type of airship combines the use of older technologies with new technologies, thereby, the lift will be obtained by combining the utilization of helium with aerodynamic lift, or, the control will be achieved by a combination of stabilizing surfaces and a multirotor system.

For years, the main problem of airships has been to obtain a stability and control system that worked in a quasi-autonomous and efficient way. Because they are large aircraft, control in urban environments or in cruise flight is a fundamental pillar to its implementation. Therefore, the fact of obtaining a system that allows a stable and precise control in all kinds of activities, both cruising and maneuvering, will be the main objective of this thesis.

A hybrid system of control surfaces with a system of rotors (quad-rotor) will be a new research line that will be studied both individually and collectively [2].

A control surfaces system in conjunction with the main motor will provide the necessary dynamic lift in cruise flight to ensure optimum control of the attitude of the airship and also to contribute to the dynamic stability. With this system, cruise flight turns similar to a conventional aircraft cruise flight, thereby facilitating the flying.

Furthermore, the four rotors system (quad-rotor) will allow vertical lift for take-off / landing and in stationary flight maneuvers, as well as a stability control form through the use of a variable pitch system in contrast to standard fixed-pitch. Fixed-pitch multi-rotor designs are mechanically simple since they are completely controllable without the complexity of the control linkages and swashplate that are inherent in traditional pod-and-boom style helicopters, but this has significant limitations in the performance of the rotors such as limitations to generate thrust in more than one direction or limitations caused by the inertia of the motor and propellers.

In this way, the implementation of a stability and control system and a variable pitch quad-rotor into an UAV (Unmanned Aerial Vehicles) will allow to get reliable results in order to its implementation in a system of large rotors for a hybrid airship, avoiding limitations of a standard control system.

1.2. Object and Objectives

The main objective of this thesis is the development and testing of a hybrid stability and control system for a hybrid airship, so that the operational requirements such as take-off / landing, stationary flight and cruise flight are satisfied. This system consists of a group of six control surfaces and a set of four variable pitch rotors. To do this, it was divided into two main parts, one dedicated to the control surfaces system and another concerning the rotor system.

Four scale prototypes were built and they allowed to simulate the performances of the airship. Thus, the first two prototypes were designed to study in depth the performance and control of the airship in different maneuvers through the utilization of the control surfaces system with real flight tests. Thus, it was possible to check the longitudinal, lateral and directional stability and control of the airship for take-offs, landing or cruise flight. Also, another main objective is the creation and later validation of different flight modes that satisfy the operational requirements.

On the other hand, the other two prototypes allowed to test the performance of a quad-rotor relative to the stability and control. This way, prototype 2 main objective is to check the performance of a variable pitch quad rotor in order its implementation in the airship. On the other hand, prototype 2.5 was built to test the performance of the airship with a fixed pitch rotor system.

1.3. Dissertation Structure

The development of this thesis begins as part of the multidisciplinary project of an airship. Thus, it is divided into five chapters.

In the first chapter the introduction of this work is presented, including the motivation, the main object and objectives and the structure of the thesis.

The second chapter corresponds to the state of the art and it contains a historical review of the different types of control and stability in airships as well as the latest advances.

In the third chapter the development of the work is detailed, including the construction of prototype 1, prototype 1.5, prototype 2 and prototype 2.5, as well as the case of study.

The fourth chapter presents a detailed explanation and discussion of the results obtained in the various tests.

Finally, the fifth chapter includes the conclusions and the future work that would be needed to continue the project.

2. State of Art

2.1. Introduction

Nowadays, creating a system of stability and control has become the main objective of development in the airship design and, specifically, in the case of hybrids Airships. The utilization of new technologies opens new lines of research for overcome the obstacle that represents the creation of a stability and control system to be effective in any operating condition.

The first airships, non-rigid, could only be controlled using control surfaces with limited dimensions and performance, since the blimp could not support heavy loads by not having an internal structure. Another problem was the impossibility of having vertical thrust, so a small runaway was needed to take off and land with the help of ten to twenty operators.

In the case of hybrid Airships, as they have an effective internal structure, allow to solve the above problems getting greater maneuverability to comply with operational requirements. Therefore, the combination of different elements such as gas lift, the multirotor system and control surfaces is presented as a promising solution.

2.2. Stability and control surfaces configuration

The first airships had a limited system stability and control and, going back to the second half of the nineteenth century we can find the first attempts of balloons that do not depend on wind currents to navigate in the desired direction. The airship Dupuy de Lome [3] was one of the first airships developed in 1872 by the engineer who gives it its name; this aircraft had a wingspan of 36 m and a 1.5 kW power engine with a speed reaching between 9 and 11 km/h. Thus, the control was performed through the engine and a rudimentary system of wires driven by several operators. In the following years, the first electric-powered airships were already made in different countries, leading to a huge increase in its popularity.

In the early twentieth century, it was probably in Spain where there were the greatest advances. On the one hand, Manuel Rivera and Sempere presented an airship which had a similar profile than aircraft and a metal internal structure, being this a very important step towards opening new lines of research and application of airships, as well as a first approximation of use of wings for aerodynamic lift in cruise flight [4]. On the other hand, Leonardo Torres Quevedo designed a new type of airship with a rigid structure, which facilitated a more stable flight and the inclusion of heavier engines. This project would lead eventually to the construction of the airship Astra-Torres, in collaboration with the French company Astra [5]. Thus, we see that these two airships represent a first approach to the concept of hybrid airship.

Nowadays, the main use of the airships that are in service is for marketing or monitoring purposes, being still a fairly marginal use. During the last two decades, different companies resumed or initiated research on different types of airships. For example, Zeppelin designed the Zeppelin NT (1997), a semi-rigid airship exclusively filled with helium. Thus, this new concept of airship will be heavier than the air with full load, being able to be lighter-than-air when the payload is low and with a very small amount of fuel. Therefore, the Zeppelin NT has three motors in order to generate the necessary thrust and, moreover, give it greater control and maneuverability. Thus, two motors will be located laterally and they will have propellers with a range of motion of 90° upward and 30° downward, so the horizontal position will be its main direction. The aft motor powers a pushing propeller that can be turned 90° downward, as well as a steering propeller directed to the side and working similarly to the lateral-thrust units of some ships. This control system is complemented by three control surfaces, which are a vertical stabilizer and two horizontal ones with a negative dihedral configuration forming 120° each one of them [6].

Furthermore, the concept called Turtle Airship (2006) results in a good approximation to the concept of "future airship". This airship has solar panels on the top, allowing it to fly autonomously over long distances. Still, its two main innovations have more to do with getting the support and with stability and control. As for the support, Turtle Airship can fly exclusively with aerostatic lift, but in case of wanting increase significantly the payload, the profile of the airship will provide aerodynamic lift in cruise flight and for low-speed maneuvers or take-off/ landing the airship has a system of electric motors, powered by solar panels, which may direct their thrust vertically up or down as needed. As for the stability and control, this airship will have a small size six control surfaces scheme; two vertical stabilizers will be placed in parallel at the top and four horizontal stabilizers distributed in a rectangular way, being a pair ahead and the other behind. This surfaces scheme beside the movable electric motors and the aerodynamic lift of the own airship create a robust stability and control system for maneuvers at low speed or stationary or in cruise flight [7, 8].

The standard configuration of control surfaces, as seen in *fig. 1,* was for many years a set of four control surfaces that are usually placed in a cross in order to simplify the control [9]. Thus, conventional airships had two rudders (one up and one down) and two lateral stabilizers (one on each side). This arrangement of the control surfaces simplifies the control of the airship because each pair controls a shaft as occurs in many conventional aircraft (aircrafts with T or inverted-T tail), so the vertical pair controls the yaw and horizontal pair controls the pitch. Despite its simplicity and fulfill its objective of changing the attitude of the airship moderately, this configuration is limited when performance requirements, operability, stability and support are greater. For example, the fact that a rudder is placed down is a ground operational limitation due to the ease of being damaged. Another important limitation is the difficulty of controlling the roll by not having flaps, which could be a problem of stability in adverse situations.

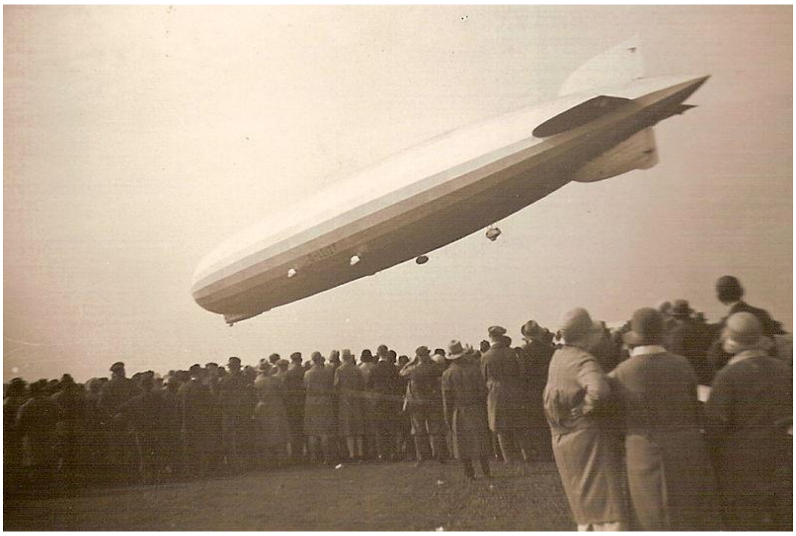


Fig. 1: LZ 127 Graf Zeppelin cross tail

In a first conclusion it could be said that the stability and control systems were very simple for decades and which represented a major limitation to the performances and usefulness of this type of aircraft. Nowadays, various lines of research seems quite promising through the utilization of more complex control and stability systems that combine different configurations of stabilizing surfaces and propellers. Thus, a detailed analysis of the stability and control is required.

2.2.1. Stability

When talking about stability is important to differentiate between two fundamental types of stability:

- Real static stability should be defined as one which exists when the airship is in constant actuation and this tends to return to its initial position immediately. The requirement for static stability defines requirements on the pitching moment slope ($M_\alpha<0$) and the yawing moment slope ($N_\beta>0$) for traditional aircraft heavier than air. For airships, it is a sufficient, but not necessary condition because some airships can be statically stable even when the yawing moment slope is negative [10].
- Dynamic stability is defined as the overall tendency of an airplane to return to its original position, following a series of damped out oscillations. In this type of stability the control surfaces still become more important to avoid abrupt transitions.

Thus, for both types of stability it can be said that an airship has positive stability if it develops forces or moments which tend to restore it to its original position, that an airship has neutral stability if the restoring forces are absent and the aircraft will neither return from its disturbed position, nor move further away or that an airship has negative stability if develops forces or moments which tend to move it further away. Negative stability is, in other words, the condition of instability. An airship with both stabilities defined as positive could operate cruise as hands-off, but in many cases, this could severely limit maneuverability.

Furthermore, it is possible to differentiate the type of stability according to the axis or the type of movement of the airship as seen in *fig. 2*. These three types of stability are lateral stability, longitudinal stability and directional stability.

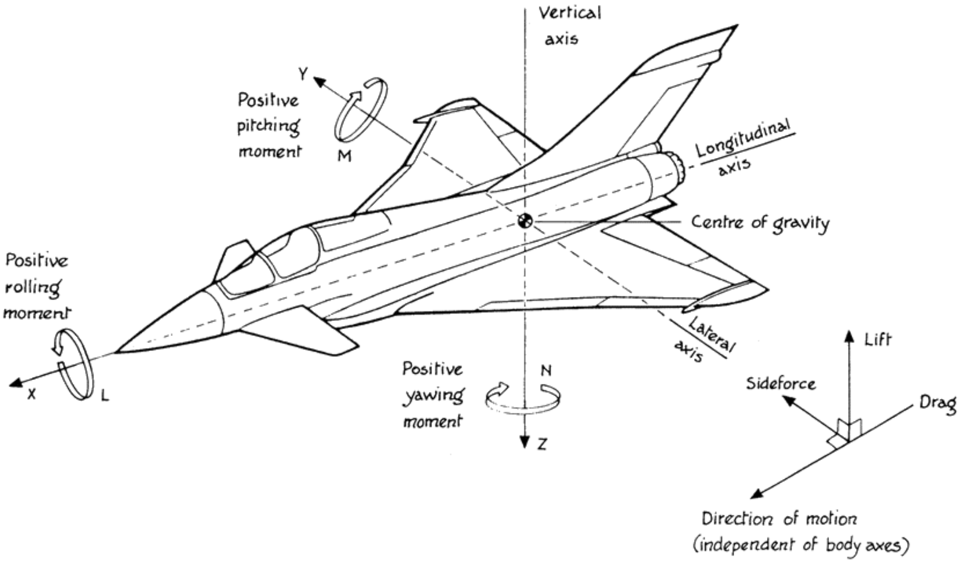


Fig. 2: Standard reference axis for aircraft, including airships.

- Longitudinal stability is the stability that occurs around the lateral axis of the airship, i.e., pitch stability. For conventional aircraft both predominant elements in longitudinal stability are the position of the center of gravity and the horizontal stabilizers. The center of gravity should be located forward of the center of pressure so that the aircraft will behave with a nose-down attitude. In the case of airships, this can make a big difficulty because of different factors that can displace the center of pressure, because it is not only necessary to pay attention to flight conditions and attitude, but rather the behavior of helium inside is an important factor to consider. Thus, this displacement of helium when varying the attitude or because of climate effects (sun in the front, rain ...) have a great effect on the distribution of the center of pressure [11].

  Conventional horizontal stabilizers are located in the tail so that when the angle of attack on the wings is increased by a disturbance, the center of pressure moves forward, tending to turn the nose of the airplane up and the tail down. The tail, moving down, meets the air at a greater angle of attack, obtains more lift and tends to restore the balance. In the case of airships the theoretical performance is similar. In a recent study the performance of a conventional configuration for a dirigible tail (cross configuration) is compared against a setting of "inverted Y" resulting in the airship has fewer longitudinal static stability at low speed [12]. Therefore, it would be interesting to maintain a horizontal configuration of stabilizers which work in the horizontal plane the same way as in the configuration in cross.

In the case of airships is vital to have into consideration an additional element in terms of longitudinal stability, critical speed. The critical speed is characterized as the speed at which attitude changes will not result in lift changes, and when crossing this speed, the elevator effect on lift reverses. For this reason some books use the term "reversal speed" for the critical speed.

Starting from the Dr. Munks' formula is possible to calculate the value of the critical speed for an airship without control surfaces [13]:

$$M_e = Volume \times 0.5\rho V^2 (k_2 - k_1) \sin 2\theta \quad (1)$$

Where k_2 and k_1 indicate the effect of gas movement inside the airship and θ is the pitch angle. The critical speed is reached when this resultant airforce equals the moment induced by the weight:

$$Wh \sin(\alpha + \theta) = Volume \times 0.5\rho V^2 (k_2 - k_1) \sin 2\theta \quad (2)$$

Where α is the angle of attack. In this sense, the critical speed is the maximum speed at which the gravity moment is able to compensate the moment induced by dynamical lift. This value will be low enough for an airship could operate safely, so introducing stability surfaces critical speed value increases significantly [9]. Tail usual configuration adds a new term to the previous equation, but other configurations would be even more efficient. If the airship is not longitudinally stable, or if in other words, it is being operated above its critical speed, the pilot must correct deviations from the chosen path as soon as they appear, while on a stable airship these deviations would be capable of self-correction if left manually uncorrected.

This critical speed should not be exceeded due to different factors. During flight both the mass and the lift will not stay constant due to atmospheric influences (sun, rain…) or fuel burn. To stay at the desired altitude, the airship can compensate for any imbalance by creating dynamic lift. If the ship is fast enough, a negative deflection of the horizontal tail surface or a shifting of masses backward will increase lift. In the other hand, at low speed, however, aerodynamic lift is much lower, but both mass and static lift are unchanged. Now the airship needs considerably more elevator deflection for the same pitch attitude change. The downforce at the horizontal tail must still be equal to that at high speed, since the static moment has not changed, and the lower dynamic pressure at low speed is compensated by deflecting the elevator by a bigger angle. Obviously, deflection angle is limited by mechanical factors and this can create dangerous situations when speed is really low as, for example, landing. A good way to avoid a crash in this situation is the application of reverse thrust combined with a positive elevator deflection which lifts up the tail.

The use of control surfaces at the front with a negative deflection lifts down the nose, so it is another good way too.

Therefore it is necessary to ensure as a project parameter that the airship would be longitudinally stable for both low and high speeds. The configuration of the stabilizing surfaces is a key parameter in order to increase his critical speed and in order to ensure a rapid and efficient response in low-speed maneuvers.

- Directional stability is the stability around the vertical or normal axis, i.e., yaw stability. The most important feature for a conventional aircraft that affects directional stability is the vertical tail surface, that is, the fin and rudder. In airships standard configuration is one upper and one lower surface on the vertical axis, although a configuration of two parallel surfaces at the top is also a good solution.

  When the rudder is set in neutral it acts as an additional fin surface, but the total fin surface isn't usually large enough to provide complete directional stability. This is quite different from the condition of longitudinal stability where stability surfaces can be locked in any position allowing the airship to return to its initial state when any disturbance occurs. As soon as there is any deviation from the straight line of flight, the air strikes on the side of the airship and sets up a moment tending to turn the airship farther from its original course. This moment corresponds exactly to the previous moment, M_e, which opposes longitudinal stability. Thus, the vertical stabilizers attempt to counteract this moment, but except for small perturbations its effect is insufficient and it should be use the rudder to recover the attitude [9].

  Therefore, vertical stabilizers must be configured and dimensioned in order to ensure the directional stability in normal flight conditions. Still, airships tend to be unstable in yaw so it is also needed special attention in the control configuration.

- Lateral stability is the stability around the longitudinal axis, or roll stability. Lateral stability is a difficult problem in conventional aircrafts. On the other hand, airships don't exhibit this problem since the static restoring moment acts with regard to roll. The only rolling motions are those due to side gusts against the airship and those due to centrifugal force when turning, but the moments of these forces are overcome immediately by the large restoring moment due to the position of the center of gravity [14].

  Therefore, airships are very stable around the longitudinal axis because of their own configuration.

2.2.2. Control

Generally one can divide the control of an aircraft as directional control and altitude control. In the case of conventional aircraft these two types of control overlap each other and are operated by a single pilot. On the other hand, traditional airships had two pilots working in coordination, one in charge of steering control and the other one in charge of altitude control. This was because of the possibility of varying the static lift of the own airship.

- Directional control is the type of control that is responsible for the course of the airship in the horizontal plane. During cruise flight the airship will hold its own course unless acted on by some exterior forces such as gusts. When this happens, it is necessary to operate the rudder in the opposing direction. If air is very gusty is impossible to predict yawing, so the magnitude of the oscillations should be kept low by pilot.

  On the other hand, the performance of the rudder or rudders will be quite limited to have an efficient yaw control, since the airships tend to be unstable in yaw. Moreover, its performance involves a complex control process to vary the direction and to correct. For example, when it is desired to turn to the right, the rudder is put over to the right. The instantaneous effect of this rotation is to produce a force to the left acting on the right side of the rudder and this force to the left has a dual effect. In the first place, it gives the moment about the center of gravity tending to turn the nose to the right and, in the second place, it moves the entire airship to the left. Both motions combine to cause the air to strike on the left of the envelope and so to turn the nose still farther to the right. This creates a centripetal force to the right so that the airship starts to move to the right creating a movement that feeds back. To avoid this situation, the rudder must be turned to the left [86]. Because of these limitations in the control, it is interesting to introduce new elements as a system of rotors that allows better control in these situations.

- Altitude control can be divided into two differentiated parts: static and dynamic. In this case, the control which turns out to be really interesting is dynamic control, because that includes control surfaces. Change in altitude is accomplished dynamically by use of elevators in conjunction with thrust of propellers [15]. To control efficiently the airship is necessary to take previously defined considerations about the longitudinal stability, taking into account the critical speed.
- There is one curious paradox in control of airships at very low speeds. It the speed falls below a certain definite value known as the "reversing speed," control becomes reversed and pulling up the elevators causes the airship to descend, although it turns the nose upward. The reason for this is that at low speeds, the air forces are entirely unimportant in comparison with the static restoring moment due to the weight when the airship is inclined [16].

> This reversing speed offers a reason for not making the static stability excessive, since reversing speed increases as the center of gravity is lowered and the resulting difficulty in control becomes more serious where the static stability is large. The phenomenon of reverse control is especially apparent if the airship is nose heavy because any attempt to lift the nose will be resisted by static moment. The decrease in the dynamic thrust downward on the nose will be less than the gain in the downward force on the elevator and the airship as a whole will descend.
>
> Anyway, different configurations, such as a system of rotors, could afford to have a high stability and deal with reversing speed problem.

In conclusion, the stability and control of an airship cannot be approached in a simple and traditional way because of all the difficulties involved, for both low and high speeds. Thus, many of the limitations of conventional airships could be saved by the development of new airships, such as hybrid airships, which incorporate new control systems that combine both control surfaces as rotors.

2.2.3. Hybrid airships

Hybrid Airships represent a new approach regarding to conventional airships. These ones combine the characteristics of the lighter-than-air airship technology and the heavier-than-air, now incorporating elements such as fixed wing or rotary wing. Thus, it is possible to open a new range of operations when overcome many of the limitations of conventional airships, as carrying huge payloads or flying at high altitude.

In a simple way, hybrid airships can be developed by attaching wings to a conventional airship. The concept takes in the considerations of the benefits of the aerodynamic lift obtained, so adding wings introduces a considerable amount of aerodynamic lift. Thus, this aerodynamic lift will join the lift created by the shape of the own airship which will have a proper size and shape for it. Finally, the contribution of the static lift will remain essential for loading most of the weight, which will be in most situations, the equivalent to the empty weight [17].

Incorporating a component of dynamic lift has many advantages, such as smaller volume, higher lift-drag ratio and flight speed, but few studies have been done on it [18]. Therefore, the system configuration of wings and stabilizing surfaces, along with a possible system of rotors should be approached both from a traditional point of view (with emphasis on the major limitations of the airships and the characteristics of conventional wings) and from a new and innovative point of view away from anything ever seen so far [19].

This way, it is possible to utilize complex systems which use dynamic surfaces for lifting and for a greater stability and control, together with different rotor configurations with the same purpose. The variety of these new configurations lies in innovation and to later validation of the model both in a practical as a theoretical way [20]. For example, a hybrid airship incorporating a tandem wings has both considerable buoyancy efficiency and higher aerodynamic characteristics initially and, after optimization, the aerodynamic characteristics of tandem wings hybrid airship are improved greatly and the lift-drag ratio is increased. Still, it is necessary to find a compromise between the dynamic lift and the drag of the airship, for this last factor not being as limiting in order to the speed [21].

As for the contribution to the stability and control of the control surfaces-wings there are still very few studies. A first comparison of a numerical study of the aerodynamic parameters of a wingless and a winged-hull airship shows that addition of a wing to a conventional airship increases the lifting force at positive angle of attack as compared to a wingless airship whereas the drag increases. Also, the winged airship has better directional stability than the wingless airship and even better longitudinal stability increasing critical speed. Moreover, the winged airship loses some lateral stability, although this is still not a problem and the airship remains stable enough [22].

In conclusion, the incorporation of a complex system of six surfaces of control could result in a good solution for improving both stability and control of the airship, as well as for obtaining dynamic lift. This system could be complemented with another system, in this case a system of rotors, to allow a better performance at low speeds and in some cruise flight situations. In *fig. 3* a conceptual design of a possible configuration of a hybrid airship incorporating six control and stability surfaces and a system of rotors is shown.

Fig. 3: A conceptual hybrid airship designed by Aeros Aeronautical Systems

2.3. Variable pitch multi-rotor system

The lack of a structure able to withstand great efforts was a big limitation in the first airships. The utilization of new technologies make possible to create hybrid airships with an internal structure designed to support efforts, so that many possibilities in order to improve control and stability are opened. Thus, the quad-rotor airships are more compact, with a more flexible control and better maneuverability, greater stability, greater lift and vertical take-off and landing, etc. [23].

As early as 1980, the US Navy together with Piasecki Aircraft built a prototype that combined a helium airship and a quadcopter system consisting of four Sikorsky-H34J. The initial concept was to increase the dynamic lift produced by the rotors when adding the static lift of the blimp so as to be able to withstand enormous payloads. Furthermore, in cases where the payload was reduced, it would be possible to use the rotors of the helicopters to get forward thrust, thereby giving the aircraft a great operational flexibility. On the other hand, the cyclic pitch variation together with the control surfaces (inverted V-tail stabilizer) provided an innovative way of control and stability. However, the results in terms of control were not expected and the aircraft crashed due to a gust of wind making the research over [24].

Another concept, in this case a more recent one, is the Skyhook JHL-40 announced by Boeing in 2008. This hybrid airship has a blimp with helium providing the necessary lift to carry its own weight and a set of four rotors that will create the lift required for the payload and, at the same time, it will propel the aircraft. The initial concept of Skyhook did not have control surfaces, although on the next designs a triangular surfaces system at tail was incorporated, reinforcing the concept of creating a hybrid control system that combines a more elaborate scheme of control surfaces together with a quadcopter.

In the last years, the number of investigations around the quad-rotor airships have been multiplied due to its load capacity, low pollution and wide application prospects [25]. Much of this researches focus on scale models and often indoor nature, in order to create the base models. This kind of models are usually small and simple structures, also having trials at low altitude and low speed. Although a priori they are quite representative models have some disadvantages such as lack of lift or less stability.

Due to the increasing popularity of small fixed-pitch quad-rotors, mainly toys, they earned enormous popularity as research platforms [26]. Therefore, the advantages, such as simple structure, low cost and indoor use, increase even more the growing research about the concept.

Most of quad-rotors used in any field are fixed-pitch due to its simplicity of control versus other types of control, even having numerous limitations. Thus, stability and control are achieved by varying the voltage provided each one of the four motors by varying the revolutions per minute (RPM) and therefore the thrust generated by each rotor.

In the last years, numerous studies have been published about different models of control and dynamics, these being supported by recent advances in miniaturized IMU technology, availability of high speed brushless motors and high power to weight ratio Li-Polymer battery technology. The convergence of many of these studies look for the simplicity of mathematical models, mainly the nonlinear ones [27-29].

The basic model of quad-copter is based on a cross configuration with four rotors connected to four DC motors, so the rotation axes are fixed and parallel. In the case of fixed-pitch, the air that flows from each of the blades points downwards to generate an upward lift. Two rotors will rotate in the clockwise direction, while the other two will do the opposite direction as shown in *fig. 4*. This configuration of opposing pairs suppresses the use of a tail rotor, as in the case of helicopters. Therefore, if the rotors operate at the same speed, the quad-copter will remain stable and balanced [30].

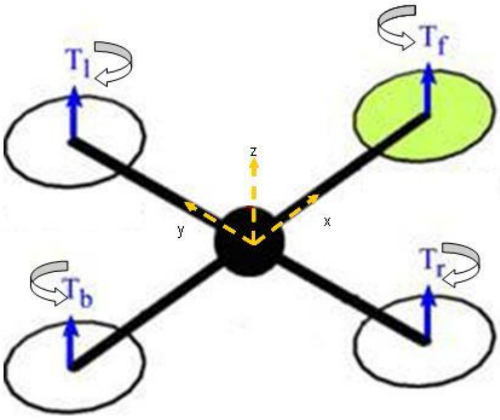


Fig. 4: Simplified quad-rotor vehicle in a stable hover

Based on this scheme, there are four basic movements to control the attitude and altitude: throttle, roll, pitch and yaw [31, 32]:

- Throttle command is controlled by increasing or decreasing the speed of the four rotors simultaneously, creating a vertical force with respect to body-frame and applied to the central axis.
- Yaw is controlled by increasing or decreasing the speed of the front-rear pair, while oppositely is changed the speed of the left-right pair. Thus, a rotation will occur around the vertical axis due to a torque imbalance caused by the fact that each pair rotates in the opposite direction. To maintain full thrust of the quad-rotor as in hovering, this command leads only to a yaw angular acceleration.
- Roll is controlled increasing left rotor speed and slowing right rotor, and vice versa, at the same rate; the other two ones remain constant. This creates a torque around the X axis causing the quad-rotor to tilt about the same axis, leading only to a roll angle acceleration to be maintained in hovering.
- Pitch works similarly to roll, but instead of varying the speed of the left-right pair, the speed of the front-rear pair is changed so while the speed of one increases, the other one decreases. Thus, a torque around the Y axis and a pitch angle will be created, while the quad-left rotor tilt around that axis.

In *fig. 5* a representation of the basic control systems can be viewed.

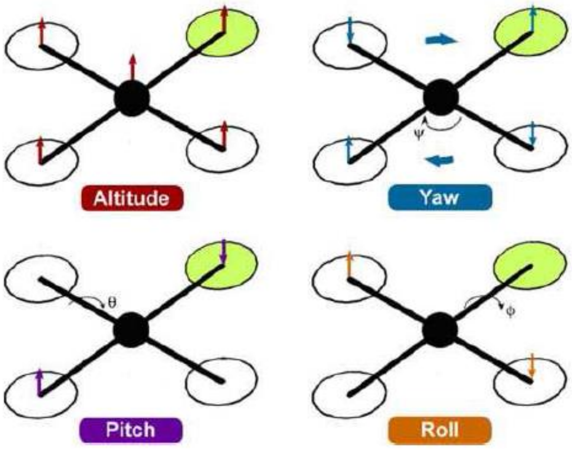


Fig. 5: Quad-rotor dynamics

The application of these mathematical and control models works perfectly for quad-rotors of small dimensions, so that the controller bandwidth may present a significant problem for the stability in the case of large models [33]. Therefore, to overcome the barrier of the 2kg of total mass of a quad-rotor is a way of approach to a large system. Some previous attempts have been relatively successful, as the case of Hoverbot [34], which consisted of four hobby helicopters joined at the tail in a cross configuration, with a total weight of 6kg. These have served as a starting point for both larger quad-rotors and variable pitch quad-rotors.

Recently, there are several cases where it has managed to fly in a stable and controlled way quad-rotors of this size and mass. The X-4 Flyer [33] was one of the first quad-rotors exceeding 4kg (4kg structure + 1kg payload) able to fly autonomously and stabilizing even outdoor. It was necessary a study and development of an efficient aeroelastic rotor design, fast motor-rotor dynamic response or robust attitude stabilization.

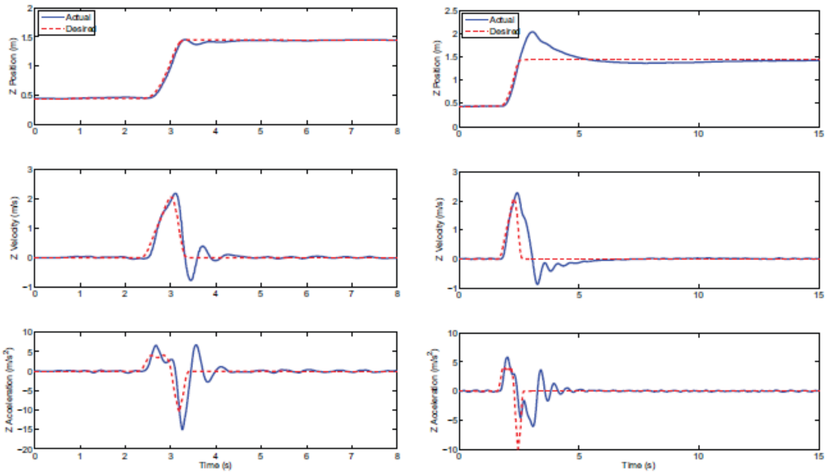
Looking ahead to the implementation of a quad-rotor system in an airship, the size of this quad-rotor will still be larger than in the previous cases. Therefore, larger quad-rotors require larger motors, which have greater inertia and cannot be controlled as quickly as small motors of the study cases. The same way when it is large enough, the quad-rotor cannot be stabilized using only RPM as a control because the torque required to change the angular velocity of the motor easily will exceed the capacity of the motor. Therefore to a major objective of stabilization in an airship, it is necessary to implement variable-pitch blades.

In the case of fixed-pitch propellers, given a constant rotational rate to the motor, the thrust produced by the rotor system will be constant, so that the only way to change the thrust will varying the voltage to the motor thereby inducing a variation in the rotational speed. When using variable-pitch blades you obtain a new degree of freedom when varying the thrust produced by each propeller, and it can be changed by varying the blade pitch or the motor RPM, although largely, it will tend to overlap. It is thus possible hover with a high rotation speed and with a low blade pitch or else decreasing the speed of rotation and increasing the blade pitch, allowing multiple combinations for the same situation [35].

The range of system performance will be limited by the maximum pitch, both physical and aerodynamic, the maximum available power and control hardware limitations.

In many situations, use variable-pitch quad-rotor has a greater advantage because of deceleration capability (being able to generate negative thrust) that for twice the effective range of thrust of each motor when compared with the equivalent fixed-pitch. The reverse thrust capabilities obtained with the use of variable pitch quad-rotor allow both inverted flight and vertical accelerations greater than gravity as well as the execution of acrobatic maneuvers effectively.

By using symmetric propellers together with a symmetrical design of the quad-rotor, this has the ability to make the same trip in both normal and inverted flight. This attribute allows tremendous flexibility in terms of maneuverability. Furthermore, one of the main advantages is the ability to generate negative thrust. While this allows the vehicle to fly upside down, it also brings the capability to decelerate quickly by momentarily reversing the propeller pitch to create thrust upwards. In *fig. 6* the better performance for a variable-pitch quad-rotor versus a fixed-pitch one in different situations is shown, getting only 1% of overshoot in the first one and 60% in the second one relatively to position.



(a) Variable-pitch flight data (b) Fixed-pitch flight data

Fig. 6: Flight data for the variable-pitch versus fixed-pitch flying the same trajectory

Drawing on the vertical flight, one of the major differences in the performance of the two types of quad-rotors is the ability to decelerate, being limited in the case of fixed-pitch by gravity, because the motor cannot reverse efficiently its direction in mid-flight and it may even saturate the actuator, which would lead to a large overshoot in the response position. In the case of variable-pitch quad-rotors, it is possible to effect great decelerations because of the ability of the rotors to switch quickly from positive to negative thrust.

In *fig. 7* the vertical tracking performance of the quad-rotor it's summarized when in fixed-pitch and variable-pitch modes, with each point representing the sum of the absolute value of the position error at each step.

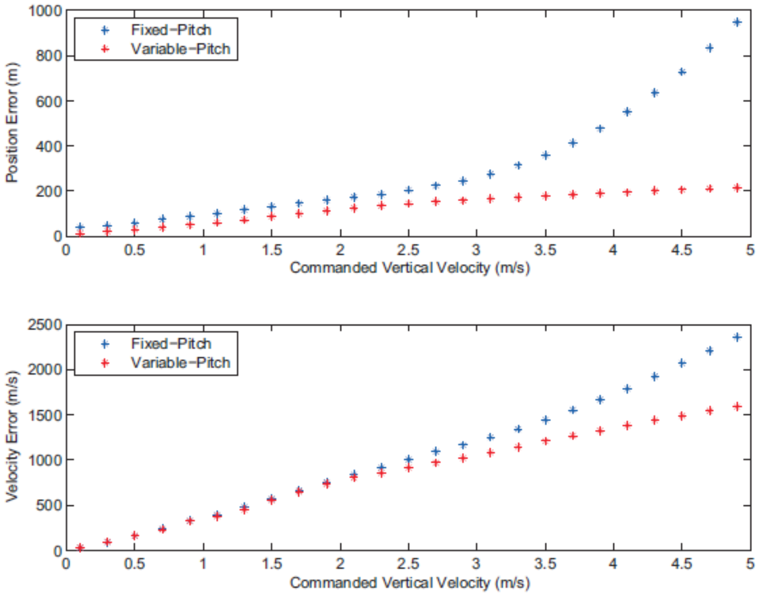


Fig. 7: Vertical tracking error

As can be seen, for low speeds both have virtually the same mistakes, but once the speed increases, the driver of fixed-pitch quad-rotor starts to saturate.

Comparing now the ability to follow a sequence of commands for linear angular acceleration, it will be only considered the roll axis of the quad-rotor. As in the case of vertical flight, the performance of fixed-pitch is similar to variable-pitch when the angular acceleration is low, while if it increases the fixed-pitch propellers begin to saturate as soon as one of the motors produces around zero thrust and the other one produces maximum thrust. Moreover, how it can reverse the direction of thrust of one of the motors, variable-pitch propeller can, at least theoretically, double the torque to the vehicle when rolling. This situation can be observed in *fig. 8*.

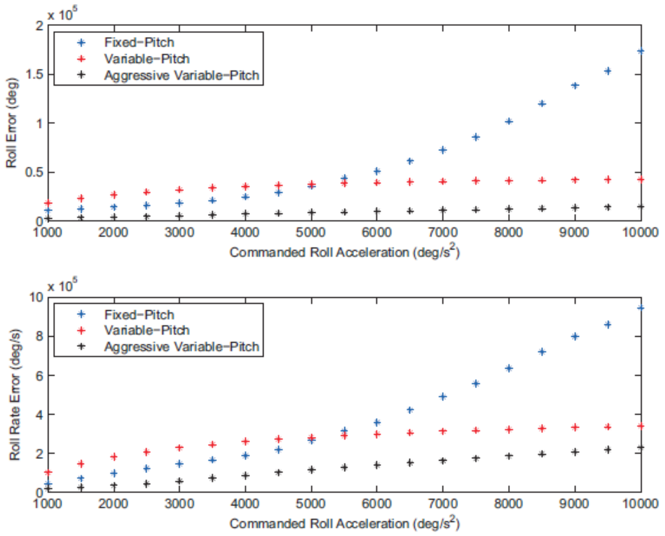


Fig. 8: Roll tracking error

As seen, when implementing this system in a hybrid airship of large dimensions, becomes vitally important to use variable-pitch quad-rotors for all its great advantages once we increase the size or speed.

When implementing variable-pitch system in an airship, a gravity, buoyancy, aerodynamic, wind resistance, propeller force analysis, etc. is required .To do this, it may be built a scale model of an airship with a similar control to a real one. Although this scale model presents a good approximation, some drawbacks occur because of the low speed and hence low stability, or lacking of buoyancy.

In contrast to standard quad-rotor, the quad-rotor airship can generate buoyancy because it has a large structure which hosts helium. This leads to be especially careful in the study of the different forces involved. Thus, the lift and weight are always perpendicular to the floor, being of special interest them to act on the same axis to improve static balance [36].

When an airship moves in the air, this in turn is moved due to disturbances, so that if the movement of the airship varies with time, then the air will also vary over time. Thus, the force that is generated by the air acts on the airship with the same module but opposite sense. This force is known as fluid inertia force and this force related to the acceleration of the airship is usually considered like an additional mass [37]. Furthermore, this force is powered due to the fact that an airship occupy a very large volume for a small relative mass. The same way, airships are susceptible to the influence of air resistance throughout the cruising flight because of their large surface, with this resistance being proportional to the speed of translation.

In conclusion, the incorporation of a system of variable pitch rotors may result in a robust solution to improve both stability and control as the lifting capacity of a hybrid airship. Even so, it is still necessary to scrutinize the behavior that this set would have in a real simulation because of the lack of previous studies in this area.

2.4. Conclusions

Through this review it is possible to draw different conclusions concerning the stability and control of airships. Historically, both the control and stability in conventional airships have been a huge constraint on its operational field and on its evolution, since problems such as difficult directional control, the limitation of the "critical speed" or the accuracy of maneuvers at low speed were difficult to solve with the technology of the moment.

Creating new configurations that apply current technology will be a good option in order to improve both stability and control. Thus, the projected six surfaces scheme allows, a priori, to improve the performance of the airship in the lateral axis and the directional one, increasing the efficiency of stability and, in the three axes, a more aggressive control is obtained, i.e., the control has an improved, wider and faster response in order to solve complicated situations caused by disruption or operational necessity.

On the other hand, this system of surfaces also provides a significant amount of dynamic lift because these surfaces work like wings in cruise flight. Thus, the design of a hybrid airship, where the shape itself could generate dynamic lift, opens another developmental pathway providing the airship with higher speed, lower volume and higher payload, among other improvements.

Incorporating a rotor system to the set will be the key to solve many limitations, especially at low speed. A variable-pitch rotor system has an improved response and a wider range of action as well as reverse thrust, as opposed to the usual use of fixed-pitch rotors. These advantages will become even more important for large rotors, as expected on large size hybrid airships.

Finally, the convergence of all these individual solutions into a common solution will be a promising way of research in control and stability of hybrid airships.

3. Case of Study[1]

3.1. Introduction

One of the main problems of airships is their difficulty for optimum control and stability. The fact of not having a high cruising speed implies that the aerodynamic forces on the control surfaces are less effective than in conventional aircraft; as well as that the source of lift is mainly caused by the introduction of helium. The combination of these two factors creates a need for a control and stability system, complex and different, in order to control the attitude and / or maintain the blimp perfectly balanced even in stationary flight.

The main concept of this hybrid system of stability and control consists of different elements. The two main parts are the six control surfaces system and the set of four rotors with variable pitch. This way, the final idea combines these two elements so that the rotors are embedded in each one of the four wings. In *Fig. 9* a simple conceptual scheme of the airship incorporating this system is shown.

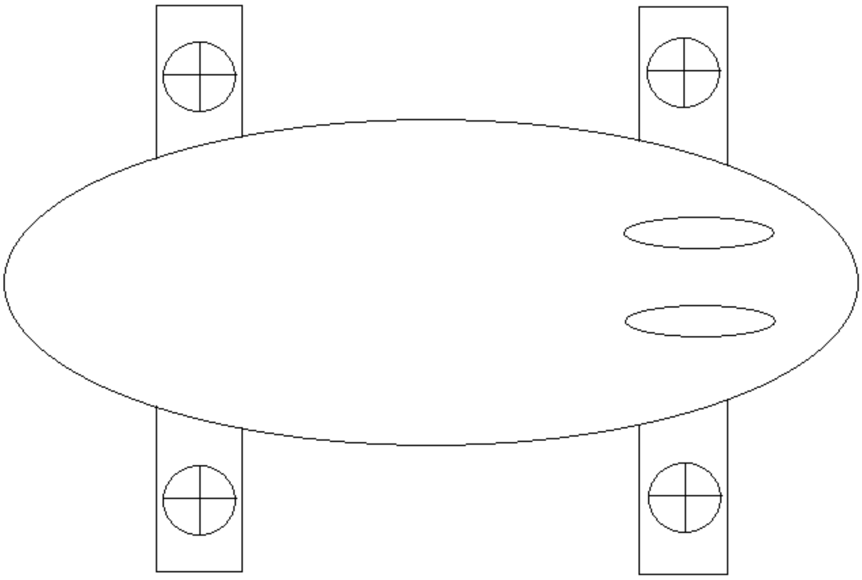


Fig. 9: Simple conceptual scheme of the airship

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[1] *Parte da dissertação relevante para efeitos do processo de proteção de invenção referido no Aviso no início deste documento.*

Six control surfaces system is formed by four wings and two vertical control surfaces. This way, the vertical surfaces are disposed in parallel in the rear of the airship and they act as vertical stabilizers and as rudders providing directional stability and control. The four wings are divided into a front pair and a rear pair where each wing is parallel to the other, forming between the four a rectangular distribution. The purpose of the wings is to provide lateral stability and control as well as longitudinal stability and control by operating simultaneously as elevator and as aileron. In addition, the contribution of the wings to create dynamic lift is also important. The profiles of the control surfaces are symmetrical because their main objective is to provide stability and control.

Furthermore, the four rotor system will be embedded into the wings also forming the rectangular distribution, which corresponds to the conventional X distribution used in quad rotors. These rotors incorporate variable pitch propellers, because as seen in chapter 2, they present different advantages over fixed pitch propellers. Moreover, each rotor rotates around an axis in order to the thrust were vectorized, but that part of the concept is included in future work. Thus, the objective of the system of variable pitch rotors is to stabilize the airship autonomously for stationary flight or at very low speed maneuvers as well as to control the airship in this maneuvers at low speed or even at higher speed ones together with the six surfaces system.

In order to successfully tackle the operational requirements (vertical take-off, stationary flight, cruise ...), it was necessary an observational study of the real behavior of the airship through different tests / trials. These two main stability and control systems were separated to simplify this observational study. Thus, four different prototypes were constructed, where two of them were utilized to test the six surfaces system and the other two were utilized to test the rotors system. In addition, three of them were a similar scale model of the conceptual design shown previously (with some simplifications).

3.2. Prototype 1

• Introduction

Prototype 1 is a scale model of the final design with some simplifications. First, this prototype does not have any internal structure, but it is the blimp itself which guarantees the shape. The other great simplification, and in this case extremely important, is the absence of rotors on the wings, being lift fully obtained by helium and dynamic lift generated by all the control surfaces.

Thus, the airship is primarily a blimp of 3.5 meters in length with a configuration of four wings and two vertical stabilizers and a pusher propeller configuration.

- **Structure and Construction**

The fundamental structural part of this first prototype consists of a PVC blimp with dimensions of 3.5 m long, occupying a volume of 3.5 m^3. So in addition to the structural component, the blimp serves another indispensable role, because it will allow to hold the helium inside and thus obtain lift. This total volume is crucial in order to calculate the amount of helium as will be seen later.

Since this is a prototype with a major dimension and a round shape, a cradle was necessary to be built in order to be able to work with guarantees. This cradle is very simple and it is based on two extruded polystyrene pieces appropriated to the blimp shape, placed in parallel (one front and one rear) where the blimp is placed, connected by two beams on each side.

The construction of the two vertical stabilizers were also made of extruded polystyrene and the profile was designed in a specific software called *Profili* and cut with a hot wire machine, by using another software called *CNC controller*. The two stabilizers are equal, with 400 mm long and 250 mm of chord, and being the aerodynamic profile the NACA 0012. Each vertical stabilizer has a moving area so you control the yaw of the airship in cruising as well. This rudder has a length of 300 mm and 100 mm of chord and it is driven by a servo embedded in the stabilizer itself. Once the two stabilizers were built, it was necessary to adapt the bottom of each one to the curvature of the blimp in order to fix on this. The fixing system should allow to remove these surfaces and it was a combination of two elements. The first element is a strip of Velcro attached to the bottom of each stabilizer with their opposite side attached to the surface of the blimp; this ensures that after each positioning they are always placed in the same position. The second element is a tensioning wire of Dynamo which can keep both stabilizers in a fixed position (relative to vertical) and a given distance, then the wire was locked at crossing each stabilizer to be attached to this with epoxy resin. Thus, the wire goes from one side of the airship to a stabilizer, from that stabilizer to another one and finally to the other side, forming a sufficiently rigid structure.

For weight reasons and because the vertical stabilizers are in the back, holes were made in the fixed part of each stabilizer in order to reduce the weight and advance the center of mass. These holes were covered with seal tape in order to maintain the aerodynamic surface.

Likewise, the wings are of extruded polystyrene, as well as the holding part that is coupled to the airship. Therefore, there are two different parts to assemble the four wings: a fixed part and a movable part, which constitutes the wing itself.

The four wings have the same dimensions, having a chord of 350 mm and a length of 600 mm. Since the four surfaces have a main purpose of control, they have a symmetrical profile NACA 0014, being able to provide lift for positive angles of attack in cruising and/or drag with negative angles. Each wing has an aluminum beam embedded into the polystyrene to allow rotation; this movement is articulated by a servo, which in this case was embedded into the fixed part and acts through an aluminum wire between the own servo and a carbon fiber piece linked to the aluminum beam part.

For the pair of rear wings the same process of holes than vertical stabilizers was made in order to continue moving forward the center of mass. According to an initial estimation, it was possible to decrease between 30-50g per wing with this operation.

Fixed parts are different for each pair of wings (front pair and rear pair), then, in addition to allow fixation of the wings, they also allow the placement of each wing (moving part) in different positions. Thus, the front pair of supports have three different positions for positioning the wings, which are defined by three aluminum pipes tubes where the beam of each wing fits. In the case of the rear supports, they have only two positions using the same system, because, as will be seen later, being away from the center of mass less variation of its position is needed to get different results. Furthermore, these supports must also be removable and have a double fixing system to ensure the rigidity of the structure in order to avoid fluctuations during the flight. The used solution was a combination of double sided tape on the opposite side of the support and on the blimp with the placement of Velcro reinforcements strengthened with a carbon fiber sheet. As carbon flexibility is limited, two curved surfaces were built on each side of the support that make the link between the two elements.

The pusher motor configuration forced the construction of a structure to keep it in a fixed position and, in turn, able to resist twisting and vibration. For this, a laminate carbon cone was built and it was fixed to the back, improving even the streamline of the airship. The cone has a diameter of 400 mm at the base and 75 mm on the top surface, where it has an extra carbon plate in order to fix the motor to that place. By being the gas inlet valve located in the same place, a removable union and easy to implement method were required. As this is a circular structure, a circular ten Velcro straps reinforced with a carbon sheet system presents a solution that meets the operational requirements. In *fig. 10*the final outcome of the piece is shown in detail once finished.

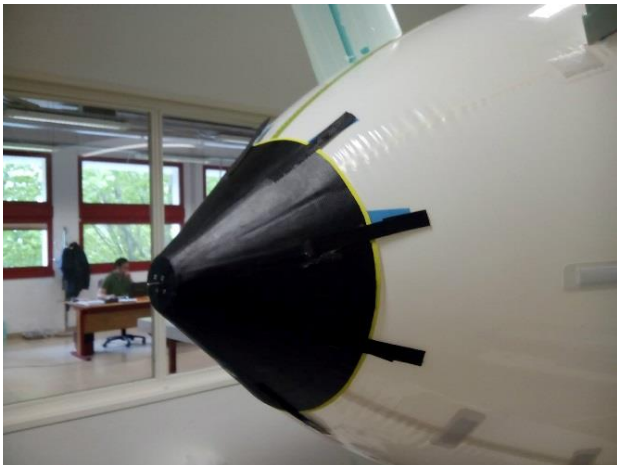

Fig. 10: Motor support built in carbon fiber composite.

The chosen motor for this first prototype was the NTM prop drive 35-48 900kv together with a three-blade propeller Master Airscrew t3020. This propeller+motor configuration ensured the power required for any performance, especially for take-off tests where maximum power available is used.

In order to control the six servos and motor a wiring distribution was placed throughout the airship, converging these ones in the same place. For reasons of the position of the center of mass, the controller, the ESC and the batteries are positioned at the front of the airship, so that the wiring joins the bottom midline and it is fixed with duct tape. Having to place these components on the front means having a set of three wires linking the motor with the ESC+Battery set traveling from end to end of the airship. The problem of this is the increased weight caused by the required thickness of the wires due to the high current which passes through them.

Finally, being a prototype for cruising, the construction of a landing gear was necessary. The landing gear is formed by two structures of extruded polystyrene placed in parallel at the bottom of the airship and with an approximate length of 1500 mm. These structures have the shape of the airship to perfectly fit to it with the use of double-sided tape. Each one of the two structures has a forward wheel and another wheel back, thus formed a rectangle of four wheels perfectly stable. To ensure the distance between the wheels, the structures were stressed with Dynamo in a similar way than used in the vertical stabilizer solution.

In *fig. 11*prototype 1 assembled without the motor support before the first tests is shown.

Fig. 11: Prototype 1 assembled without motor support

- **Six surfaces distribution, Lift and Center of Mass**

To calculate the lift obtained with helium it was necessary to estimate the total weight and the total effective weight, that is, filled with helium. According to the manufacturer's specifications, the blimp has a capacity of 3.5 m^3, so that capacity harboring helium inside would get a maximum lift of approximately 3.5 kg, which will give us a reference to the real value.

As it can be seen in *table 1*, the weight of each one of the components that go into the airship is presented along with the 3 batteries that were utilized. For design reasons, some components are already mounted on the blimp and assembled in its final form.

Table 1: Mass of components

Component	Mass (kg)
Battery 2.2	0,202
Yellow Battery	0,186
Battery 4.0	0,341
Motor+Propeller+Cone	0,347
2xComplete Wing	0,354
2xHoled Wing	0,296
2xVertical stabilizer	0,209
Landing Gear	0,321
Blimp+Wires+Supports	2,477
ESC	0,117
Maximum Mass	4,850

This brings the total maximum mass to 4,850 kg. This value falls within the initial estimations where a total of 5,000 kg maximum weight was estimated. Once assembled all the components and with the airship filled with helium it was possible to calculate the maximum effective weight. These values can be seen in *table 2* obtaining an estimated 30,215 N of lift. Thus, the lift obtained is within the expected range, being the obtained lift 86% of the estimated maximum lift. This difference is due mainly to the difficulty of calculating the amount of helium in the airship, the real percentage of helium gas in the bottle and the gas losses that the airship suffers by having an elevated pressure.

Table 2: Lift and max weight estimation

Maximum Effective Weight	17,97 N
Maximum Weight	47,578 N
Estimated Lift	30,215 N

Moreover, the mass of each component will be crucial to calculate the position of the center of mass. A priori, it is possible to make different estimations of the position of the center of mass with the above items, for example, by different combinations of batteries and being able to dispense with the motor-propeller-cone set.

The fact of having a large blimp filled with helium greatly complicates the theoretical calculations of the center of mass. This is mainly due to the own weight airship distribution and the helium distribution inside this, having zones of different pressure and, therefore, a non-uniform distribution of mass. Thus, the initial idea is to position the center of mass coincident with the point of application of the lift (center of buoyancy) which will be approximately at 33% of the length according to the manufacturer of the airship. As can be seen in the following *tables 3 and 4,* we have two theoretical situations where placing the center of mass close to that desired position is achieved.

Table 3: Center of mass position for maximum weight

Component	Mass (kg)	W(N)	x(m)	W(N.m)
Battery 2.2	0,202	1,982	-1,166	-2,31
Yellow Battery	0,186	1,825	-1,166	-2,13
Battery 4.0	0,341	3,345	-1,166	-3,90
Motor+Propeller+Cone	0,347	3,404	2,380	8,10
2xComplete Wing	0,354	3,473	-0,810	-2,81
2xHoled Wing	0,296	2,904	1,720	4,99
2xVertical stabilizer	0,209	2,050	1,940	3,98
Landing Gear	0,321	3,149	0,460	1,45
Blimp+Wires+Supports	2,477	24,299	-0,250	-6,07
ESC	0,117	1,148	-1,116	-1,28
Maximum Weight	4,850			0,01

Table 4: Center of mass position for motorless configuration

Component	Mass (kg)	W(N)	x(m)	W(N.m)
Battery 2.2	0,202	1,982	-1,106	-2,19
Yellow Battery	0,000	0,000	0	0,00
Battery 4.0	0,000	0,000	0	0,00
Motor+Propeller+Cone	0,000	0,000	0	0,00
2xComplete Wing	0,354	3,473	-0,76	-2,64
2xHoled Wing	0,296	2,904	1,79	5,20
2xVertical stabilizer	0,209	2,050	2,02	4,14
Landing Gear	0,321	3,149	0,52	1,64
Blimp+Wires+Supports	2,477	24,299	-0,2	-4,86
ESC	0,117	1,148	-1,106	-1,27
Total Weight	3,976			0,02

As can be seen, one situation corresponds to the assembly with all elements (three batteries and motor), then needing a lift of approximately 17,97 N. In this case the center of mass is located 1/3 of the length of the airship (1166 mm from the start), where theoretically also the static lift arm is situated. The other situation corresponds to no motor testing, enabling moving forward the center of mass approximately 100mm; this advance of center of mass will facilitate longitudinal control working positively to prevent nose-up. A combination with battery 2.2 reduces the total weight 0,874 kg, so that the effective weight is reduced by nearly half, being in this situation 9,398 N.

As explained previously the airship has a six surfaces system with the idea of having an excellent control and stability. In *fig. 12* a representation of the position of the four wings and the two vertical stabilizers is shown.

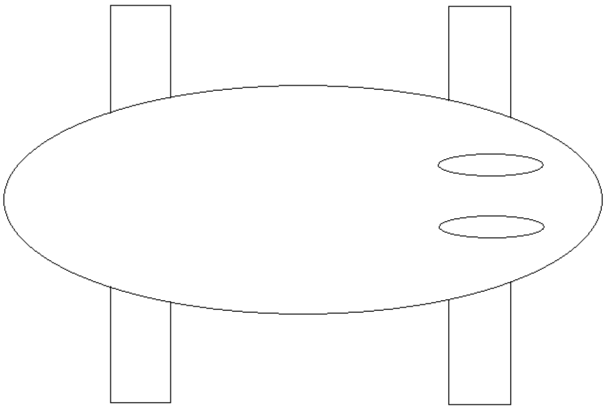

Fig. 12: Positioning surfaces scheme

As can be seen, a pair of wings is located at the front of the airship and the other pair at the back at approximately the same longitudinal position as the two vertical stabilizers. Since the position of each pair of wings is variable, they can be placed in different positions in order to adjust the location of the center of mass or to vary its efficiency. So, the front pair can be

300, 500 or 700 mm from the nose of the airship and rear pair at 2800 or 3000 mm also from the nose of the airship. Likewise, the stabilizers are located at 2900 mm.

Once all design parameters are defined (profile, position, size ...) the calculations of the lift needed for different conditions can be made again. This way, from the C_L values for each angle of attack of the NACA 0014 profile used, it is possible to approximate the lift obtained for different speeds using the following equation:

$$L = \frac{1}{2}\rho V^2 S C_L \quad (3)$$

Where S is the total surface of the 4 wings. Thus in *table 5* we can see the lift obtained according to flight speed and angle of attack considering the four wings are working simultaneously.

Table 5: Estimated lift for different speeds

	Speed (m/s)	Lift (N)	Mass (kg)
alpha=5	5	8,445	0,861
	6	12,160	1,239
	7	16,551	1,687
	8	21,618	2,203
alpha= 7	5	10,097	1,029
	6	14,540	1,482
	7	19,791	2,017
	8	25,850	2,635
alpha=9	5	11,401	1,162
	6	16,417	1,673
	7	22,346	2,277
	8	29,186	2,975

As can be seen in the above table, the values are simple estimations of the total lift that we could get considering that cruising speed and flight parameters are not fully defined to be a study of stability and control. Therefore, based on the projected value of 7 m/s it is observed that for not very high angles of attack in take-off, the lift necessary to support the actual mass is obtained. Still, in this initial phase of testing it would be advisable not to exceed 10 degrees of angle of attack due to possible problems with longitudinal stability.

The configuration chosen is really interesting because of the possibility of using the four surfaces independently, varying their angle of attack one to one or coordinated in pairs. Therefore, it would be possible to define different angles of attack for the front and rear pair obtaining multiple combinations of lift and attitude.

- ## Flight Modes

It is possible to configure a number of modes or flight modes in order to test the airship's performance in terms of control and stability.

On one hand, the configuration of the two vertical stabilizers is independent from the four wings even though they work simultaneously. Thus, the control of the two stabilizers is in a parallel way, i.e., both work together and are used through a single channel to be merged using a physical union (adapter) responding accurately to control commands .

To control rotation about the longitudinal axis, the roll motion, the pair of wings of each side operates simultaneously, i.e., if the right pair increases the angle of attack then the left pair reduces it. This type of control is very efficient because, on one hand, four control surfaces act simultaneously and, having control surfaces in two different positions (front and rear), rolling occurs in a stable way with respect to the lateral axis. Therefore, creating a flight control mode to mix this configuration with software was required, because in this case (and in every one including the four surfaces) it is not possible to utilize physical connections between each other due to the need to combine different flight modes.

Regarding the longitudinal attitude control, three standard flight modes were planned with the main aim to facilitate control in real flight tests. A priori, it might seem unnecessary to create different flight modes having the option to control each surface independently, but there are two major limitations when running this: the complexity of the control command and the pilot's difficulty to control so many variables efficiently and almost instantaneously. So the three flight modes are described below:

- ## Flight mode 1: four synchronous surfaces

The first flight mode is basically the fully coordinated movement of the four control surfaces, that is, any variation in the angle of attack is produced simultaneously in each one of these surfaces. This configuration allows to maintain a flight attitude not very aggressive with changes in the angle of attack, which in case of being small it only raises or lowers slightly the airship. The fact of controlling simultaneously four surfaces creates a uniform lift distribution in the two pairs of surfaces, being optimum for minor corrections of the attitude in cruising flight. This mode is also used in both the take-off and landing because of, for example, the take-off objective is to maximize the lift of all surfaces simultaneously.

Furthermore, due to aerodynamic effects there is a possibility that the front pair of wings exerts aerodynamic shadow over the rear pair, thus creating an asymmetry in the lift of each pair. However, as the estimated flight speed is not very high (since part of the lift is generated by helium) these variations should not be a problem if present, but it should be a factor to be monitored. Thus, one should also be aware that how the lift is created in different positions and from different sources, the effective position of the arm of the lift may vary along the longitudinal axis of the airship.

Within this flight mode, it is also possible to vary the neutral position of each pair of wings, i.e., that instead of keeping the neutral position corresponding to an angle of incidence of 0°, this angle of incidence could be positioned different to 0° (positive or negative) in a pair of wings or even in both. This variation of the neutral position creates an asymmetric distribution of lift and drag in order to correct constant pitch attitudes, i.e., the lift created by the front pair of wings would be different to the lift created by the rear one. Although the neutral position is different, the variation of the angle of incidence is the same for all four control surfaces.

- **Flight mode 2: symmetrical surfaces relative to the lateral axis**

This second mode of flight could be considered the opposite to the first mode. It consists in varying the angle of incidence of the front pair symmetrically with the rear pair using as a focal the lateral axis of symmetry of the airship. Thus, a positive variation of the angle of incidence at the forward pair results in the same variation, but negative, in the rear pair. Therefore, it is possible to create lift in the rear pair and increase the drag on the front (or vice versa) displacing the effective position of the arm of the lift backward (or forward in the opposite case) and thus producing the variation in the pitch attitude of the airship.

The main objective of this flight mode is to aggressively change the attitude of the airship being able to create large variations in pitch as quickly as possible. This type of control so aggressive can be very useful to correct the behavior of an aircraft such as an airship, because due to low cruising speed and low density together with its large volume, it tends to have an unstable equilibrium above certain angles.

Similarly as in the first flight mode, the effects of aerodynamic shadow of the front pair with respect to the rear should also be considered, especially for high negative and positive angles of incidence. It would also be possible in this mode to change the neutral position of each pair of control surfaces.

- **Flight mode 3: combination of modes 1 and 2**

The third flight mode is a combination of the two previous flight modes, mode 1 and mode 2. Through a complex programming of the control command it is possible to make a quick transition between the two modes of control. The details of each one of the above modes are again repeated in this mode, adding only a small difficulty in the transition from one control mode to another. Thus, the main limitation is the pilot’s difficulty to operate the control commands quickly and effectively again.

The objective to combine the two previous modes of flight is mainly motivated by the necessity of having a kind of aggressive control (mode 2) and a kind of control that maximizes the lift (mode 1). For example, in a take-off in runway the first mode would be necessary to take-off and the second mode for controlling the attitude of "nose-up" just after leaving the ground, triggering a negative angle of attack on front pair and a positive one in the rear pair.

3.3. Prototype 1.5

Prototype 1.5 turns out to be a continuation of the first prototype with some structural modifications. With this model, it is also expected to reduce substantially the weight to carry out tests to real performances in flight where the necessity of generating dynamic lift is secondary. In this way with reference to the tests of prototype 1, it was yet possible to determine more accurately the real performance of the airship when incorporating six control surfaces.

• Structure and Construction

As the prototype is a modification of the first prototype, the focus here is on the modifications introduced to reduce the weight and improve the performance, being the blimp again the main structural part where the rest of the components were fixed.

The most important change in terms of weight reduction comes from the six control surfaces, from being constructed in extruded polystyrene to be built in balsa wood. Thus, as it can be seen in *fig. 13*, the structure is now formed by a set of ribs attached to a spar in the line of maximum thickness. The front part, which ends at the spar, was closed to form a torsion box. Finally, this structure was covered by a thermo retractable film on both sides thereby obtaining an excellent finish that respects the airfoil.

Fig. 13: New control surface structure

The vertical stabilizers have the same dimensions as those present in the prototype 1. Regarding the stabilizers airfoil, they kept the NACA 0012 profile previously used. The big difference in this modification is that the stabilizers do not have any moving parts, being the stabilizers themselves fully articulated at its base. Therefore, it is guaranteed that the moving area is much bigger, providing an effective directional control except for high angles of sideslip where stall may be a problem.

Furthermore, the wings slightly modified their dimensions moving from having a length of 600mm to 500mm and a chord which is now 300mm instead of the previous 350mm. This reduction in size is conditioned because by reducing the total weight, the necessity of generating dynamic lift is lower and, at the same time, this reduction in size of the four wings also means a slight reduction in weight. In this case, they keep the same profile previously used, this being a NACA 0014.

Another important change is the method of fixing the six surfaces to the blimp. The chosen solution was the same for all six surfaces and it allows a significant reduction in weight. As in this prototype it is not essential to experience the different positions of the wings (this will be done in the trials of the first prototype) it is possible to design a piece subject to a fixed position and which articulates each one of the control surfaces. In *fig. 14* the design of this new piece of support can be seen. So, it has a main part where the servo and a satellite part which serves as support are located. The idea of creating the support into two parts is that you can adapt it to the shape of the airship, so it is possible to ensure that the servo is kept in a fixed position and perpendicular to the surface by fixing both sides with two strips of carbon fiber.

Fig. 14: Control surfaces support

To build the support two possibilities regarding the construction method and the materials were analyzed: 3D printing plastic (PLA) and balsa and plywood using a laser cutter. On the one hand, 3D printing ensures a robust single piece and manual work was only cleaning the waste of printing, but otherwise to print a support takes about 13 hours. The total weight once assembled was 44.3 grams. On the other hand, cutting the wood pieces is faster with laser, but it required some work to assemble each one of the parts of the support. The weight of the support once built was 29.7 grams. Therefore, as the construction time and quality are almost the same, the weight prevails as the main factor of choice, being used the solution in wood.

As for the motor configuration, the cone-shaped structure built in carbon was used again, with the difference that the motor-propeller group is replaced by one that is lighter and also less powerful. This change is conditioned by the need for lower power because of the reduction of the overall weight of the airship, and almost no required power to operate on the ground. Thereby, a significant reduction in weight at the rear is achieved, which is also beneficial for the location of the center of mass. The motor utilized is a RcTimer 750KV outrunner brushless BL 2830-14 along with a two-bladed propeller 9”x4.7".

Wiring distribution was made similarly to prototype 1 by placing the ESC + 1 battery again at the nose of the airship. By replacing the motor by a lighter and less powerful one was also necessary to change the ESC, but not the wire that connects them and that runs along the bottom of the blimp. It also dispensed with the previous landing gear and it was just placed a removable three wheel tricycle distribution. This change was motivated by the different types of tests that this prototype will have compared to the first, since it is virtually restricted of ground operations. Thus, it was possible to simplify this part and reduce weight.

As for the configuration of the control surfaces and flight modes, the same configurations of the study done in prototype 1 was reused. This way, the wings were placed in the same position as the optimum position of the previous prototype and flight modes are exactly the same without any variation. The final assembly of prototype 1.5 can be observed in *fig. 15* in order to compare the modifications with respect to prototype 1.

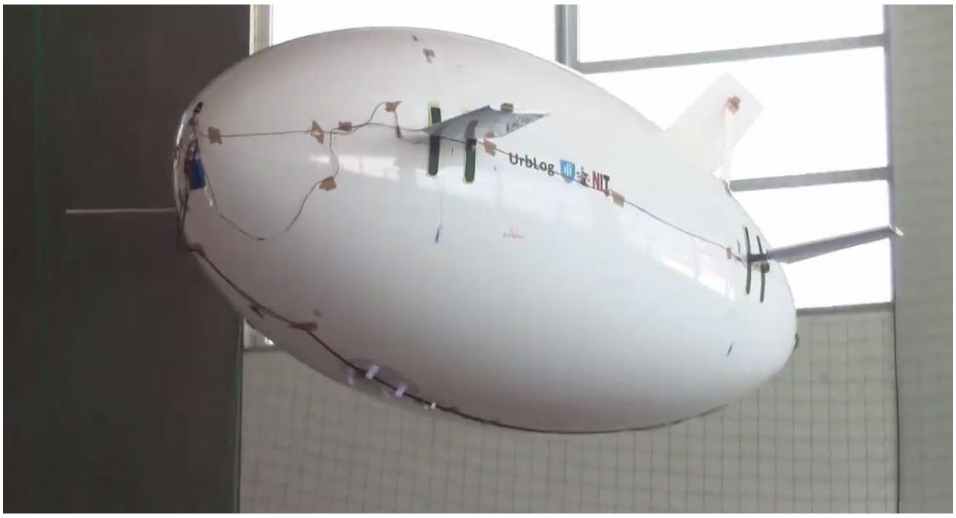

Fig. 15: Final assembly of prototype 1.5

3.4. Prototype 2

Prototype 2 is completely different from any of the other prototypes, since this dispenses with the use of the blimp. Thus, this new prototype will have a frame where four motors will be joined with variable pitch propellers placed in an X distribution. The main objective of this prototype is to verify through tests the response and behavior of utilizing variable-pitch rotors as opposed to standard fixed pitch ones.

- ## Structure and Construction

The main structure that supports all the components is the frame X666 from Hobbyking, which is formed by a central carbon structure divided into three parts and four aluminum beams (two black and two silver to facilitate identification) where the motors were placed at the tips.

In *fig.16* the motor together with the mechanism used for variable pitch is shown. This configuration was utilized for all four motors and to each motor is fixed a pair of propeller blades. The operation of the mechanism is simple, at the lower end of the beam a servo is placed which displaces this beam and, this way, it also changes the pitch at the other end of the beam. Therefore, it is possible to control the pitch of each motor propeller individually according to what was explained in chapter two.

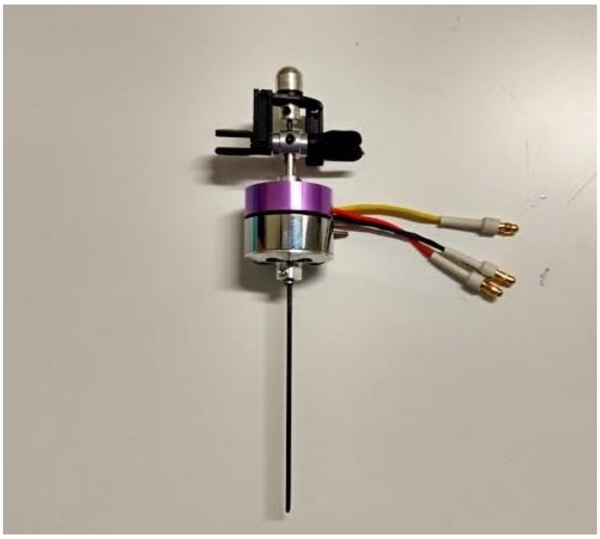

Fig. 16: Motor together with the mechanism used for variable pitch

Each one of the motors was connected to the central structure using two wires. One of them is the servo wire and it goes to the plate and connected to the receiver, having independent control for the pitch of each motor. The other cable was attached to each ESC first and then to the central area where they join each other before being joined to the plate and the receiver.

In f*ig. 17,* a simplification of the quad-rotor used is shown, so in this case it does not present any wires or electronic components, having only the frame, the motors and the variable pitch propellers. Thereby, it is easier to identify the most important components.

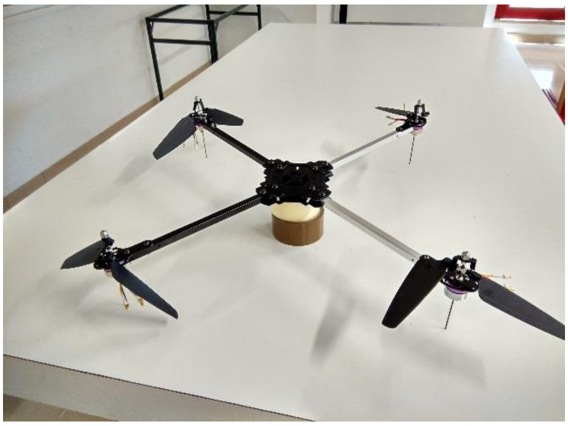

Fig. 17: Quad-rotor simplified without wires and electronic components

3.5. Prototype 2.5

Prototype 2.5 is a combination of the structure of prototype 1.5 along with the rotor distribution of prototype 2. The aim of this prototype is to test the performance of the rotors system together with the blimp and thus simulate different types of performances.

- **Structure and Construction**

The structure of this prototype is virtually the same as that of prototype 1.5, since the main change was the replacement of the four wings for the fixed pitch rotors. In this case, four fixed pitch propellers were used in order to simplify the control and because they allow the use of an auto-stabilizer controller, which allows to test how an auto-stabilizer solution works for an airship. In this way each one of the rotors was placed together with each support used for the wings in prototype 1.5. These supports have a new piece at its end that replaces the part where the servo was previously placed. Into this new piece the aluminum beam tip fits perfectly and each rotor was positioned at the opposite extreme, being thus possible to reuse much of the wiring. By having now motors in the position of the wings, the wiring set (three) needed to supply each motor had to be added the same way as it was done in prototype 2. Even so, it was necessary to change the servo controller relative to prototype 1.5.

By having now a new propulsive system it is possible to dispense the back motor, which was removed with the carbon cone greatly reducing the total weight. Furthermore, the two vertical surfaces placed in order to improve directional stability of the airship are maintained or not depending on the type of test.

In this prototype the position of all the batteries, ESC and receiver was modified from fully forward position that it had in the first two prototypes. Because of significantly reducing the weight in the rear, now the position is slightly ahead to 1/3 the length of the airship. This way, the center of mass was maintained at the same place and, in addition, this allowed to save some weight when placing the cable distribution of the rotors. At that place, a nacelle was placed to host the different electronic components explained above and this way it was also used as ground support, so the landing gear was dispensed with.

In terms of control mode, it is used the same as in prototype 2 in order to obtain new results of the performance with rotors , but in this case using the blimp for support and fixed pitch to simplify the tests. *In fig. 18* prototype 2.5 assembled is shown during the tests.

Fig. 18: Prototype 2.5 assembled

3.6. Conclusions

The construction of the previous four prototypes is crucial in order to be able to perform flight tests. Thus, the first two prototypes focus on the study of the system of control surfaces and they aim to study different flight performance such as take-off, landing or cruise flight. To do this, the different parts described above were built, so that they were sufficiently strong and light and that fulfilled the operational requirements. In this section the programming of the different flight modes to be used in flight tests was also carried out.

The other two prototypes are aimed to study the system of rotors. With prototype 2, an approach to the utilization of variable pitch rotors through the constructed model was made. In the case of the last prototype, the rotor system is coupled to the airship after the construction of a fixing system, so as to allow a first study of the behavior of the system incorporating rotors.

4. Results[2]

4.1. Introduction

In this chapter, the different tests for the four prototypes are explained. This way, prototype 1 and prototype 1.5 allowed to test the stability and control of the airship with the six surfaces configuration. On the other hand, prototype 2 tests were useful to confirm the performance of a variable-pitch quad-rotor face to implement it in the future. Finally, the prototype 2.5 was a first approximation to the performance of the airship with the embedded system of rotors. In this case, as explained previously, four fixed pitch rotors were used in order to simplify the control and because they allow the use of an auto-stabilizer controller.

In a global way, the ultimate goal of this set of trials is to implement in the future a system that combines the six control surfaces with the variable pitch rotors system, thus creating an optimum stability and control configuration for an airship from the study of the two parts separately.

4.2. Prototype 1

• Stability and control tests results

Once the preliminary study of control and stability was made, doing flight tests of the first prototype presents a fundamental way to check if the model designed and built is valid. For this, different types of tests were made in order to attempt to isolate the performance of the various control surfaces and different rotation axes of the airship. On the other hand, tests on ground (running) and tests of take-off/landing and flight were also differentiated, since it is vitally important to guarantee the performance in any given situation.

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[2] *Parte da dissertação relevante para efeitos do processo de proteção de invenção referido no Aviso no início deste documento.*

Because of operational and space limitations, the running space for take-off was reduced, so that the flight tests are partially limited even being sufficient to test what was previously established. Thus, for shortening this running taking-off distance, gliding tests and with less weight were made, where the airship was driven by an operator. Even though it may seem a rudimentary method, it is quite effective because of the reduction of the speed required to take-off due to the weight reduction. Moreover, this reduction in weight at the rear (motor + propeller+ cone) allowed new options for disposal of the center of mass, as if necessary, it could be advanced or turned back with a larger margin of maneuver. Likewise, it is possible to set the position of the wings in different ways, so both pairs were at the most forward position of each support for the first two groups of tests, i.e., the front pair were placed at 300 mm from the nose and the rear one placed at 2800 mm from the nose. For longitudinal stability tests it is where this variation of position really becomes important because of the location of the center of mass and the location of effective lift arm generated by all of the four control surfaces.

• Directional stability and control

The main objective of this tests is to check the performance of the two vertical surfaces in order to stability (operating as stabilizers) and control (rudders). These vertical surfaces were placed at 2900 mm from the nose as explained previously. Thus, the first tests were run on the ground in order to check the stability supplied by the two vertical stabilizers. These first tests consisted of different runs with stabilizers and without them, being able to verify that the behavior was stable when they were placed, but became totally unstable when removed, causing different sudden and unpredictable movements around both the vertical and longitudinal axis. After seeing the need to have stabilizers on the ground , take-off and flight tests were tried with the same previous conditions, presenting many problems of control without stabilizers before and during take-off and then, becoming uncontrollable once in the air. Thus, it is possible to determine that having vertical stabilizers (two parallel in this case) is fundamental in order to have good stability both on the ground and in flight.

Furthermore, the moving parts of the two vertical stabilizers were also tested as part of the control system, and more specifically, of yaw control. To do this, the method was analogous to previous trials beginning on the ground and followed by take-off and flight tests. As noted above both control surfaces work simultaneously allowing a more efficient control.

The first test on the ground showed an inefficient control when using these moving surfaces (rudders), obtaining a slow response. These conditions become adverse when controlling a blimp, because a quick response and in many cases an aggressive one are needed to control the attitude. Thus, the tests were repeated in take-off and flight situations obtaining the same results as on the ground.

Therefore, dimensioning and construction of a new rudder was necessary to allow an effective yaw control. Thus, two movable parts were constructed for each stabilizer maintaining the leading edge length of 300 mm, but with a symmetrical swept back, obtaining 200 mm at the trailing edge. The greatest change takes place in the increase of the chord, which goes from 100 mm to 250 mm in order to oversize the effects of the rudders. Given this increased size of each rudder, this should lead to increased weight in the case of using the same polystyrene again, so these ones were built of Depron (a lighter extruded polystyrene foam) thereby maintaining the initial weight.

After installing the new rudders, the previous tests were repeated. In the ground runs it was now possible to verify that the system of two parallel control surfaces went back to be as effective for control as it had been previously for stability, giving the airship an immediate response, since it was necessary obtaining an improved response to correct adverse attitudes. In the take-off and flight tests the results were again as expected, therefore, once rudders were resized, a perfectly efficient control is obtained.

It is important to consider the fact that it was necessary to increase the area of movable surfaces of both surfaces, because it shows that the performance of an airship, even at half load, is far from the usual parameters of most common aircraft.

• Lateral stability and control

Tests for lateral control and stability followed the same pattern as above, with the difference that in this case the four wings were simultaneously stabilizers and control surfaces. The fact of having a symmetrical profile is optimal in order to obtain greater stability and a symmetrical control for positive to negative angles. As seen above, at this time the programmed control system has great significance for control, so that the surfaces work two to two (right pair and left pair), since they will allow a change in roll maintaining the airship stable.

Thus, the first tests were again running on the ground in order to check the stabilizing effect of the four wings. To do this, the same tests were made both wingless and with them, being the tests with wings in a neutral position (0 degrees). Analogously to the tests of the vertical stabilizers, similar results were obtained, as we have a laterally stable behavior with wings, but one unpredictable and unstable when without them. By obtaining these results on the ground, it is obvious that to ensure the stability in the air without any of the four wings is impossible, even in the case of helium provides all the lift and it were possible to dispense with the lift generated by the wings in cruise.

The stability tests in flight were exclusively winged due to operational requirements, because it was necessary to generate some lift with them. Thus, lateral performance was the desired for either situation confirming that the model of four surfaces distributed in the same plane and symmetrically around the airship works as expected, since the airship always remained with a stable and virtually neutral position relative to the lateral axis.

The lateral control trials began again run on the ground. The control mode was used to vary the angle of attack of the right pair and, oppositely, the left pair in order to maximize control. In this case the ground tests were limited due to the fact that, by running over the landing gear, the airship could only roll a little around the longitudinal axis. Still, it was possible to check that small variations in attitude occurred quickly and without disruptions in the performance of the airship.

To avoid these limitations, take-off and flight tests were made, since in-flight the airship has complete freedom of movement in terms of rolling. The results obtained for the simultaneous combination of the four wings were as good as expected, allowing an immediate and very stable response to any command. In addition, if necessary a more aggressive control with larger attitude variations can be used, for example, to get the airship out of any dangerous attitude or to quickly correct the position.

• Longitudinal stability and control

The latest trials, involving exclusively an axis, focused on longitudinal stability and control. As in previous cases it started with stability tests, but this situation is difficult to completely separate the control of the stability by the type of maneuver. When running on the ground the airship had a good behavior when it had four wings in a neutral position, remaining perfectly stable and free from pitch up. When the airship did not have wings, the same behavior as during rolling analysis was observed again, since the tests that were made are exactly the same. Thus, the airship presents abrupt changes in attitude especially when speed is increased.

Regarding the performance of stability in flight, it can be said that the airship has a stable behavior once it is very close to the equilibrium (level flight) and as long as no major changes in pitch attitude are observed. That is, the model of four surfaces gets to maintain level flight if small perturbations occur, but when these disturbances become larger the active control is necessary to correct the attitude.

For control tests, we started from different flight modes, emerging then the need to differentiate each one of them, obtaining results for running, take-off/landing and flight, as well as for different configurations for the position of the wings or the presence or not of the motor.

▪ Flight Mode 1

The first flight mode corresponds to the synchronous movement of the four wings and, the same way as in the previous tests, the airship continued with a configuration of the wings in its foremost position. It began with on ground tests in order to check if the control was enough to vary the pitch attitude for both positive and negative angles. The results showed that, despite the limitations of operating on the ground, this control mode got to vary the attitude of the airship in a slightly aggressive way while maximizing lift or drag. Performing feints of take-off/ landing, i.e., that the airship leaves the ground a few centimeters, it was checked as the first flight mode is good enough to take-off, because apart to maximize lift, the airship maintains a reduced pitch attitude allowing a fairly level take-off.

After verifying the effectiveness of the first flight mode in performances close to the floor, it was necessary to repeat these operations in situations of real take-off and flight. The first trials were with built-in motor, so that the total weight of the airship was high if we incorporate the three batteries in order to place the center of mass in the right position. As the available space for running was limited, it was only possible to test take-off maneuvers. In the first test with the maximum weight the airship took almost 75% of the available distance to reach the speed necessary to take-off, but once reached that speed and maximizing the angle of attack of the four wings it took-off perfectly. As might be expected, this control mode presents a huge problem after take-off because a large pitch angle is created and the pitch attitude of the airship becomes uncontrollable even trying to maximize the angles of the surfaces. According to a video analysis of different attempts, it was possible to check that for a pitch angle greater than 10° the airship becomes uncontrollable. In *fig.19* the pitch angle created during one take-off maneuver is shown.

Fig. 19: Pitch angle created during takeoff maneuvers for flight mode 1

To attempt to resolve this issue, different solutions were adopted. The first one was to lighten the airship removing some weight from one battery and, then, from another one. Lightening the airship, the lift needed for takeoff was lower, so the angle of attack required was lower too. This way, the center of mass was moved slightly aft. Thus, the airship gets to take-off with a smaller pitch angle, but as well as without one or without two batteries the previous situation occurred again due to the position of the center of mass.

The next solution experienced was the creation of an asymmetric distribution of the lift moving the effective arm backward and creating a slightly nose-down moment. This way, the front pair was set with a negative angle of incidence of 5 degrees, so the rear pair had always a higher angle of incidence. Therefore, the rear pair generates more lift than the front one for positive angles of incidence. Tests with this configuration showed a mild improvement in the pitch attitude, but the airship remained uncontrollable. These results indicate that this approach could be effective in the case of creating an even more rearward distribution, but this could lead to problems in the level flight condition. Similarly, these tests were repeated by placing the pair of rear wings in the rearmost position, but how the center of mass was also displaced backward, the foregoing problem was repeated.

A different solution is to remove the cone + motor + propeller carrying out tests driven manually by an operator. When removing the back propulsive structure it was possible to do tests without two batteries reducing the total mass in 0.874 kg and keeping the center of mass in the same position. Placing again one battery was also possible to move the center of mass in a more forward position. The first tests with this solution were with only the battery 2.2 in order to reduce as much as possible the total weight of the airship. Thus, the previous behavior of nose-up was repeated just after take-off although in a much milder form mainly conditioned by the slower speed. Therefore, the batteries were added again to advance the center of mass even more and try to avoid such exaggerated pitch attitude. With the addition of the yellow battery the mass was increased in 0,186 kg at the nose displacing the center of mass forward about 150 mm. The tests were repeated getting practically the previous results, since the displacement of the center of mass was small. However, by placing also the battery 4.0 (which added 0,341 kg), the center of mass was displaced about 325 mm to the front from its project position and the airship had stability problems due to this, i.e., although this gets to partially solve the pitch angle increase just after take-off, the nose responds to control in a violent way, resulting in an unpredictable performance and, usually, in a nose-down moment. Therefore, to advance the center of mass too much was not a good solution to correcting the attitude which took the airship after take-off.

After testing different solutions it could be concluded that the control of the airship with the use of mode 1 is not feasible due to the inability to take control of the airship after take-off. However, the performance on ground and during the start of take-off indicates that it may be a perfectly viable flight control mode in cruise if major disruptions do not occur.

▪ Flight Mode 2

The second flight mode corresponds to the symmetrical movement of the pair of front wings with respect to the rear pair. This flight mode is primarily intended for an aggressive response when varying the angle of attack of the wings. The first test were ground tests where the angle of the front pair was positive and the angle of the rear one was and vice versa, i.e., the angle of each pair varies oppositely to the other pair. When running and the angle of attack of the front pair was increased (and lowering the rear pair) the attitude of the airship corresponded to a very quick increase in nose-up moment and in tail-down one, whereas if the opposite control was activated (i.e., lowering the front pair) an attitude of nose-down and tail-up was observed. These attitude variations were those expected and they are characterized for their aggressive control to change the attitude of the airship if we maximize angles of attack, so this is especially useful for correcting complicated situations.

Through start of take-off tests it was again possible to confirm these results. In this case, it was possible to adjust two different settings for take-off. The first one was with positive forward angle and with negative rear angle in the wings, so that the lift was generated in the front pair while the drag was generated in the rear pair; this situation displaced the effective lift arm very forward, in addition to that, its module was much lower than when using mode 1. This reduction in lift requires an increase in speed or a reduction in weight to be able to take-off, so the no motor configurations explained in the previous cases was used. The first take-off test was with only the battery 2.2 to minimize the mass to a total of 3,976 kg. The obtained results are the expected ones based on prior experience and theory. Thus, the pitch angle increased much faster than for the same configuration by using the first mode, turning the airship fully uncontrollable. This result was repeated for the other two battery configurations. By adding the yellow battery (0,186 kg) the performance was virtually the same and, in the case of three batteries (+0,527 kg), a slight improvement was observed in the reduction of this attitude because the center of mass moves forward about 325 mm.

Since it is unfeasible to take-off keeping the control in the same position or making minor corrections, an experimented solution was to try to reverse the angle of attack of each pair of wings to move the lifting arm towards the back and try to level the airship. After testing with the same previous settings, the results showed that due to low speed (start of take-off), the lift generated at the rear and the drag at the front pair was not enough to compensate that pitch moment.

The second configuration was taking off with an angles of attack of the wings opposite to the utilized in the previous tests, that is, the angle of attack of the front pair was negative while the angle of the rear pair was positive. This configuration generates lift at the rear pair, so that the effective arm was situated at the back of the airship. In the same way as for the first configuration, the different possibilities of weight distribution and center of mass were used by placing or not the batteries. The first tests were with the battery 2.2 (the center of mass were placed at 1106 mm from the nose) showed that the use of this configuration did not let the airship to take-off in a normal way, since it had an attitude of negative pitch angle (nose-down). Therefore, it is not feasible to use this configuration to take-off though it could be perfectly feasible for level flight. Further testing is necessary on that. The tests with the other two battery configurations worsen even more the attitude when taking off due to the displacement of the center of mass forward, discarding completely this second configuration.

The results for the second control mode showed the impossibility of its utilization for take-off due to its problems of attitude, both nose-up in the first configuration and nose-down in the second. Still, tests on ground, and even some tests during take-off, indicated that the flight mode is feasible to correct sudden changes in the attitude of the airship due to its aggressiveness. This would allow us to get out of difficult situations or to correct extremely quickly the attitude during cruise flight.

▪ Flight Mode 3

The third mode of flight is a combination of the previous two modes. This required the creation of a set of commands that allows the transition from one mode to another quickly and intuitively. Thus, the tests focused on getting an efficient and fully controlled take-off and cruise flight. In order to reduce the overall weight and to place the center of mass in a favorable position (985 mm from the nose of the airship), the no-motor configuration was used with batteries 2.2 and yellow at the nose, so the total mass was reduced in 0,688 kg.

The control scheme used was the following; first mode 1 is used to maximize the lift during the start of take-off. Then, once the airship was completely in the air and with an attitude of nose-up still small it was changed to mode 2 of control maintaining the angle of attack on the rear pair of wings, but deflecting the front pair of wings to that same angle but negative. Thus, it was possible to compensate the nose-up moment created by displacing the lifting arm backwards and creating high drag in the forward pair of wings. As it was an aggressive control, the airship quickly changed its attitude allowing to maintain a level position once finished the take-off maneuver, giving way again to control mode 1 for cruise flight and leaving mode 2 to counteract major disturbances or, if necessary by the type of mission, abruptly changing the attitude of the airship. Once level, flight mode 1 responded perfectly to the small variation of angles of attack of the wings (positive and negative) allowing up and down without any complications. Using this mode it was possible to make a slow descent in order to landing without using mode 2 at any time.

As we can see with the tests performed, control mode 3 turns out to be a perfect solution for controlling the airship being almost limited only by the skill of the pilot. The combination of the two modes can solve efficiently the problems in the take-off in an easy way and, once the airship is level, mode 1 ensures longitudinal control in a standard cruise flight, being able even to use mode 2 if that extra aggressiveness is needed in control.

• Full control

The latest tests attempted to gather the three types of tests previously explained by combining all the control variables (6 surfaces) and simulating real conditions performances. Due to space constraints it was only possible to simulate small flight performances and not a long cruise flight to fully experience each and every one of the variables of stability and control.

In this way, numerous take-offs and landings were performed obtaining stability and control based on previous tests. Some combinations mixing different types of control were also experimented by using vertical control surfaces with the four wings at the same time, such as a round flight or direction corrections during take-off, in order to extend from an observational way the information obtained previously.

After completing the tests, we can conclude that the devised scheme with six stability and control surfaces gives many guarantees to maintain the airship stable in cruise flight and that using mode 3 we also have an efficient and reliable control for almost any situation.

4.3. Prototype 1.5

Once first prototype tests were done, it was possible to focus the following tests on complementing the previously ones. This second prototype is lighter than the first one, so it is expected to make complete cruise flight tests and even landing tests. As the dynamic lift necessary was lower it was also possible to do some tests with lower speed in order to check if the blimp got into "reverse speed" and, when it occurred, studying different solutions to overcome this situation. Furthermore, in case the speed used with the first prototype were maintained, it is possible to experience an even more aggressive control than in prototype 1, so since this one has a smaller effective weight, this second prototype is more sensitive to a control command of the same magnitude.

- **Flight tests**

The first tests was completed using the structure described above in chapter 3, that is, the six control surfaces and the motor assembly, mainly. The yellow battery was the first battery configuration used, so the center of mass was slightly moved backwards from its ideal position. This way, the airship was released slightly upwards by an operator to start from a stationary position in the air, because it was close to fluctuate due to the reduction in weight with respect to prototype 1. Thus, it was possible to observe how the airship increased its pitch angle too much due to the position of the center of mass, being almost impossible to recover it from that attitude. Therefore, the yellow battery was replaced by battery 4.0, moving the center of mass about 140 mm (approximately to its ideal position) by adding 0,155 kg at the nose. The results obtained with this configuration were quite limited despite the airship had an optimum balance. This is because the increased weight is substantial, then this one is far from the expected fluctuation condition (i.e., effective weight close to zero), rendering the motor not powerful enough to accelerate quickly and be able to control the airship.

To reduce the total weight, the following tests were made without the two vertical stabilizers and their structure, reducing the mass in 0,160 kg at the rear of the airship and allowing greater flexibility to position the center of mass without excessively ballasting the front of the airship. Thus, the yellow battery was used again, but then, the center of mass was already located close to its design position. The tests performed with this configuration consisted of a small launch of the airship upwards by an operator and, once balanced in the air, the motor was operated to the maximum. In this way, the airship made a straight line flight in order to check the effect of the four control surfaces , being possible to test the effectiveness of the control for both roll and, especially, for pitch. The results obtained relative to roll showed a similar control to which was obtained with prototype 1 (very effective, but it creates an important yaw component), but in this case limited by the absence of directional control, which should be used to compensate for inappropriate attitudes. On the other hand, longitudinal control was able to recover significantly large nose-up and nose-down attitudes using mode 3 as in tests from prototype 1. The simultaneously variation of the incidence of the four surfaces was sufficient to perform small changes in pitch attitude and the airship responded to these control commands very quickly and accurately, but being very important not to create pitch angles greater than 5° to avoid divergence. Yet, these results were greatly limited due to the lack of directional control and stability by having to remove the vertical control surfaces, therefore, the airship became easily uncontrollable directionally, limiting these tests.

As the directional stability and control were already studied in depth in prototype 1, a new simple system was designed to obtain at least the directional stability to redo, with greater guarantees, the previous tests. In this way, a set of two Depron stabilizers was placed in the same position where the vertical control surfaces were previously, also respecting the same dimensions and adding 0,066 kg. As they are constructed with such a light material, the adjustment necessary to maintain the center of mass in the same position will be simply to change the previous battery by battery 2.2 along with 60g of lead, which were also placed in the nose. Moreover, a new system of tensile strings of Dynamo was used to keep the stabilizers into a fixed position and, likewise, the end of each wing was also stressed in order to maintain the horizontality in the neutral position.

The tests performed with this new configuration was similar to the preceding ones, maintaining as main objective the study of the behavior in flight. In this way, the airship was thrown again upwards by an operator and, from a balanced position in the air, the motor was commanded. The new tests under mode 1 showed once again that the airship remains stable and controllable in cruise flight as long as there were no major disruptions that should be compensated, because it fails to recover the airship of large nose-up attitudes with this mode. In order to try to prevent these situations, a new asymmetric configuration of the angles of incidence of the wings was created, keeping the rear pair in neutral position (0 degrees) and setting the neutral of the front pair for various negative values. The behavior of the airship was a nose-down attitude for smaller angles (about -5°), while for angles close to -2° there was only a small improvement for low speed, since for higher speeds the above situation was repeated.

Thereby, the flight mode 3 is presented as the only possible alternative to get a good control in any given situation. To do this, flight tests were made again with this configuration. By having now vertical stabilizers, the behavior of the airship was directionally stable, avoiding the random behavior of the above tests. The results obtained for these final tests showed a good longitudinal control of the airship because it is able to change from a smooth control to a much more aggressive one, so, using this aggressive control the airship responds quickly and abruptly getting to recover from almost any attitude or no desired disturbance. Despite the fact that the control seems to be a promising way of research, it is necessary to continue with new tests in order to adjust the control and stability, because sometimes unwanted and difficult to predict behaviors are observed. In *fig. 20* the airship is shown during the last tests for flight mode 3.

Fig. 20: Airship during the last tests for flight mode 3

Throughout this group of tests, the phenomenon of "reverse speed" was observed for low speeds. As seen above, this phenomenon originates the opposite function of the control surfaces when the airship speed is below of this "reverse speed“, being an important design parameter which should be reviewed in order to develop a final prototype as it was shown in chapter 2. Still, by having four control surfaces and an aggressive control it is possible to reduce the module of this theoretical speed, avoiding any problems for standard performances.

In conclusion, the results obtained from the prototype 1.5 confirm the observations made based on the data obtained with the first prototype. Thus, mode 3 seems to be a promising way in a system of six control surfaces. Similarly, this system of six surfaces provides the ability to have an aggressive and reliable control for almost any attitude. Finally, the incorporation of a system of rotors is presented as a good addition to the control surfaces, and it can be expected that by operating together, the control of the airship will be total.

4.4. Prototype 2

In order to confirm the behavior seen previously, various tests were made with prototype 2. In this way it was possible to get a real simulation of the performance of a quad rotor using variable-pitch rotors. These tests were quite simple as just an empirical confirmation of in situ operating is expected. Therefore, two types of tests were made. The first tests were with the quad rotor embedded in a spherical structure in order to check the stability. The second ones were level flight test with the main objective of studying the control of the quad rotor.

• Flight tests

The first tests consisted in simulations where the quad rotor was embedded in a structure. In *fig. 21* the structure used for these tests is shown. This is composed of two wooden rings moving each one of them along two different axes creating a sphere. Thereby, the quad rotor moved in any of the three axes while remaining fixed. This type of test was particularly useful for studying the stability of the quad-rotor and check if it was possible to recover from certain situations. In addition, these tests served as a first step for future tests where the quad rotor will have a software which will auto stabilize it.

Fig. 21: Structure utilized for testing the prototype 2

The second test consisted just in small flight tests to prove the efficacy and reliability of the control by altering the variable pitch. Thus, these second tests showed a normal performance of the quad rotor, resulting in a precise and reliable control. In the case that it was necessary, the quad rotor responds aggressively with major changes in the pitch of any of the propellers. This aggressive control is especially useful for correcting strong disturbances once it is implemented in the airship, specially creating reverse thrust. Furthermore, the yaw, roll and pitch control are done the same way as for a fixed pitch rotor corresponding with the e the explanation made in chapter 2.

The obtained results show that the use of variable pitch rotors allows the quad rotor to easily recover from slightly pronounced attitudes, being necessary a more aggressive response to control bigger attitudes. So, the next step relative to the investigation will be repeating this type of tests in order to create and verify the operation of a software that auto-stabilizes the quad-rotor for its future implementation in the airship.

4.5. Prototype 2.5

The main objective of the test for prototype 2.5 is to obtain a first approach to what the real performance of an airship with a rotor system embedded is like, making different tests for both manual control and for automatic control that auto stabilizes the airship. To simplify these tests, motors with fixed pitch propellers were used instead of variable pitch propellers, and the results were a nice empirical study and a good initial approach to check if fixed pitch propellers are enough to control the airship.

- **Flight tests**

Before making flight tests with the airship filled with helium, tests with air inside the airship were made. Therefore, the first tests were performed on the cradle with the motors with fixed pitch propellers and the airship filled with air. In *fig. 22* the airship is at the cradle where these tests were made.

Fig. 22: Airship at the cradle during the first tests

The main objective of this kind of tests is to check the structural impact when the rotors are incorporated to an airship with no internal structure. In this way, it was possible to study the performance of the supports in order to maintain the position of the rotors fixed and to avoid vibrations. By using air, the airship remained over the cradle at any time, even close to the maximum power values, since the air does not provide static lift.

At the very beginning of these first tests a structural problem was observed, because the support of each rotor did not get to maintain the position once they generate a small amount of thrust. This situation is due to the absence of an internal structure in the airship and its ease to deform against great efforts. Furthermore, the system of stringers positioned as explained in chapter 3 maintained the position in the opposite direction to the weight, that is, it resisted perfectly stresses caused by the movement of the rotor and the structure. Thus, a similar system of stringers were placed in situ just as previously described, joining the end of each rotor support with the underside of the airship.

Once these new stringers were placed, the supports gained enough rigidity to maintain the position for small amounts of thrust. Then the motor power was increased gradually, being possible to observe the appearance of small vibrations in all motors. By passing about 50% of the maximum power, these vibrations acquired a significant magnitude and started to compromise the structure of the support, especially the area where the motor was mounted. Thus, different tests were performed where 50% of the maximum power of each motor was exceeded separately and all collectively, obtaining as results the breaking of motor's support (also breaking the propeller when impacting with its own support) of three different motors in different performance. Similarly, structural damage was also observed in some of the pieces that are part of the support, particularly at the junction of the support with the aluminum beam.

These results showed a significant vibration problem by incorporating a rotor system to an airship with no internal structure. Theoretically it is possible to prevent occurrence of this problem by reinforcing the external structure of the set of the supports and the fixing system of each motor to the aluminum beam. Furthermore, by using air as the gas, the objective was to test the performance of the structure for big loads. Replacing the air by helium the airship gets almost all the lift necessary to maintain stationary flight, so that the rotors are needed just to maintain stability and to perform variations of the attitude, so that the power required is significantly lower.

Once the air tests were made, the airship was filled with helium to carry out the second group of tests. The main objective of these tests is to check if the use of a system of fixed pitch rotors is viable in an airship by using a controller that help to stabilize it. Thus, the airship was mounted the same way as in the previous figure and it was placed again on its cradle. Furthermore, the fixations of the motors were reinforced with screws and the tensioning system was slightly extended in order to reduce the preceding problem of vibrations. Anyway, as the airship was close to fluctuate, the power required was much less than that used in previous trials, avoiding, at least theoretically, the occurrence of vibrations.

The tests performed were vertical take-offs from the cradle and with the main objective being to check if the airship rises in a stable way with the help of the auto stabilizer. Even before starting to rise, the auto-stabilizer tried to keep the blimp leveled increasing the power of some of the motors and presenting in this situation certain problems to do it. When further increasing the power and starting the maneuver of vertical take-off, the airship began to oscillate (not immediately) with a roll movement from side to side which was increased more and more, that is, the auto-stabilizer increased the power in a side to remain the airship leveled, then the airship reacted violently to this power increase with a rolling movement around the longitudinal axis. Thus, the power had to be increased even more on the opposite side to counter this roll, so that the response of the airship was a new rolling movement, but to the opposite side. This phenomenon was continuously repeated until the power of the rotors made the airship to react in a way that it could even turn around.

This situation is mainly due to two factors. The first one is the inability to create reverse trust with fixed pitch rotors, so that the rotor system requires the presence of gravity to be leveled in order to descend the opposite side when the power is increased. The second factor is the own nature of the airship, because as it has a large volume with a high skin friction and a small effective weight, the effect of gravity upon the airship is minimal, thereby preventing the stabilization.

Therefore, based on the results obtained with these tests it can be concluded that the implementation of a system of fixed pitch rotors on an airship is virtually impossible if this had a very low effective weight relative to its total volume. Therefore, the incorporation of a system of variable pitch rotors could resolve this situation thanks to its faster, more effective and able to create reverse thrust control, thus making the help of the weight unnecessary. In this way, implementation of the system of variable pitch rotors on the blimp seems to be a good line of research to achieve an efficient and reliable control and stability.

4.6. Conclusions

After analyzing the results of different tests for each of the prototypes, it is possible to conclude that the solution presented throughout this thesis is a promising way of research and development in order to obtaining an efficient and reliable control and stability.

Thus, from the tests performed with prototype 1 it was possible to prove the effectiveness of six control surfaces designed previously. In addition, the performance of the airship for different flight modes was also studied, highlighting the success of the flight mode 3. With the tests of prototype 1.5 it was possible to reaffirm the results of the first prototype. This way, it is expected that incorporating a rotor system to the six surface system, the airship would be adequately controllable. Therefore, it is necessary to continue the investigation and tests around this promising concept.

The results obtained for prototype 2.0 confirm that a distribution of four rotors is a good solution in order to improve stability and control. By incorporating variable pitch propellers it is possible to obtain a much more aggressive control, which will be of great interest for the feasible implementation in this type of airship. The latest tests, corresponding to prototype 2.5, showed the performance of an airship with a configuration of four embedded rotors. The first tests were performed with air and above a cradle in order to check the performance of the assembly formed by the rotors and the blimp. The results obtained show vibration problems when power above 50% is used due to the absence of an internal or external structure. When replacing air with helium it reduces significantly the power required so it is possible to avoid this phenomenon under normal conditions. In addition, it is possible to conclude that the airship becomes uncontrollable when using fixed pitch rotors since it goes into a cyclical oscillating movement as it is expected from theory shown in chapter 2. Therefore, it is necessary to study the implementation of a system of variable pitch rotors to be able to control the airship.

Finally, we can conclude that the general system studied has promising potential to stabilize and control the airship. From performed tests where the two solutions are studied separately it will be possible to develop new tests where the system of six control surfaces with the system of four variable-pitch rotors will be combined. Thus, it is possible to obtain a complex, reliable and efficient system of stability and control.

5. Conclusion

5.1. Dissertation Synthesis

Nowadays, airships are generating a growing interest, but they still have numerous limitations. The development of new technologies has allowed hybrid airships become a reality, multiplying the number of research on them. In this way, numerous lines of research are opened in all areas of project of airships and, especially, this will allow the development of stability and control systems that are truly efficient.

In chapter two was presented the state of stability and control fields of airships. Different tails and stability and control configurations were studied through its historic development. Then, a deep study of the stability was made including lateral stability, directional stability and longitudinal stability. This study explains the behavior of airships in terms of stability and the different limitations and their possible solutions. Similarly, it was also made a full study of control. To overcome this limitation in the stability and control there are numerous possible solutions such as introducing hybrid airships. Therefore, a new concept of a stability and control system was proposed. This system is a combination of two elements: a distribution of six control surfaces and a set of four variable pitch rotors. Finally, a systematic review about quad-rotors was made to check the feasibility of using this configuration for controlling a hybrid airship, as well as the utilization of variable pitch rotors instead of the common fixed pitch ones.

For that, four different prototypes were built and they were explained in chapter three. Two of them are a scale model of the airship aimed to test the stability and control of all surfaces. The construction process was explained for both airships, including different estimations of the six surfaces distribution, the lift and the weight. In addition, the configuration and operation of the flight modes for the six surfaces distribution were explained in detail. The third one is a quad-rotor to analyze the behavior of a variable-pitch solution and its configuration was explained in detail. Finally, the last prototype is a scale model again, but this time aimed to test the performance of a quad-rotor airship with fixed pitch control.

The results from the different tests show this concept is a promising way to stabilize and control a hybrid airship. First prototype tests validate a new mode of control which solves different problems related to the stability and control. This new mode corresponds to mode 3, resulting in a combination of mode 1 and 2. According to the results from the second prototype tests, the third mode allows full control for different types of performances. This includes performances in ground, take-offs and landings and cruise flight. Even so, it is necessary to continue the investigation of this concept as well as its implementation along with a system of rotors in order to get an even better control.

The results from prototype 2 tests confirm that the use of variable pitch rotors allow the quad-rotor recovers easily from slightly pronounced attitudes, being necessary a more aggressive response to control bigger attitudes. The same way, it is important to continue the research for implementing an autonomous system that stabilizes the quad-rotor. According to results from prototype 2.5 with air, when exceeding 50% of the power of the rotors, the blimp has vibration problems. This phenomenon could be theoretically solved by incorporating an internal or external structure. In addition, the power required for common performance is much lower when utilizing helium instead of air. On the other hand, the utilization of a system of fixed pitch rotor is not viable for an airship because it goes into a cyclical oscillating movement and it becomes incontrollable.

Finally, one can conclude that the combination of a system of six control surfaces with a system of four rotors with variable pitch is a promising way to stabilize and control a hybrid airship.

5.2. Concluding Remarks

In this work the proposed objectives were reached showing that a six surfaces configuration together with a variable pitch rotor system is a valid new concept to greatly improve stability and control. Six surfaces configuration and flight mode 3 improves critical speed and therefore, the behavior in relation to longitudinal stability and control. Considering a configuration that will solve this limitation was a huge effort and numerous tests were required, since nose-up moment is an inherent big problem of airships, but even so the results obtained are very promising. This combination also guarantees an great lateral stability and an improved control mode. After overcoming some problems, the pair of resized vertical surfaces ensures lateral stability and provides good directional control solving the problem of directional control explained in chapter two by turning the two surfaces into completely moving ones. In conclusion, this six surfaces solution guarantees an improvement of stability and control compared to traditional systems in many aspects.

Furthermore, the use of a system of fixed pitch rotors together with the airship is not a feasible control solution because this becomes uncontrollable by not being influenced by gravity nor having reverse thrust on the rotors. It is also possible to conclude that for high motor power, the overall airship with the system of rotors experiences vibration problems by not having internal or external structure. Still, the use of stringers solves slightly and efficiently many of the problems caused by the absence of said structure. Finally, the system of variable pitch rotors seems to be a good alternative to traditional systems, displaying numerous advantages such as the ability to create reverse thrust or obtaining a control with an improved response.

In conclusion, this new concept is a promising way, but still must be studied in depth both individually and combined system of six control surfaces and the rotor system.

5.3. Prospects for Future Work

Due to the current work and acquired knowledge and experience it is believed that the next steps in this work should cross the following investigation lines:

- Derive the equations of motion of such an airship and study its stability and control characteristics
- Perform a parametric study on the size and position of the wings and rotors to optimize the stability characteristics and control response of the airship
- Continue studying in depth the system of six control surfaces
- Test the system of variable pitch rotors together with the airship
- Create a software that autonomously stabilizes the variable pitch quad-rotor
- Develop a new configuration that combines the six surfaces scheme with the variable pitch quad-rotor
- Study the feasibility of this new concept for larger airships
- Test results obtained in larger scale models
- For new prototypes, try to quantify certain design parameters as the critical speed or reverse speed

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