Modern Airship Design Using CAD and Historical Case Studies

A project present to
The Faculty of the Department of Aerospace Engineering
San Jose State University

in partial fulfillment of the requirements for the degree
Master of Science in Aerospace Engineering

By

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approved by

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Modern Airship Design

MSAE Project Report

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MSAE Thesis / Project Evaluation Form

Title		
Name		Semester
Advisor		

Scale: 1/5 = Lacking 2/5 = Weak 3/5 = Acceptable 4/5 = Good 5/5 = Excellent

	Max Possible Score = 100	Max Possible	*Weight*	*Ave score*	Project Advisor	Faculty 2	Faculty 3
1	Application of mathematics appropriate for graduate level and the problem	5	*1*				
2	Application of AE science (aerodynamics, propulsion, flight mechanics, stability & control, aerospace structures & materials, etc.) and/or aerospace vehicle design, appropriate for graduate level	20	*4*				
3	Use of modern tools (computational or experimental)	10	*2*				
4	Appropriate literature search (# and appropriateness of references cited)	10	*2*				
5	Understanding of the cited literature (summary of previous work)	10	*2*				
6	In-depth analysis and / or design of an AE system	20	*4*				
7	Correct language and terminology	5	*1*				
8	Ability to summarize (abstract) / draw conclusions	5	*1*				
9	Appropriate use of graphs and tables	5	*1*				
10	Clear project objectives	5	*1*				
11	Appropriate modeling	5	*1*				
	Total Score	100					

Overall Score: 90 – 100 = Excellent, 80 – 89 = Good, 60 – 79 = Acceptable, 40 – 59 = Weak, 00 – 58 = Lacking

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Abstract

This project has two main goals. Firstly it aims to identify if there is a market need for this type of aircraft in the modern aviation and aerospace industry. Report will highlight the practical applications of airships in the field of civilian and cargo transport today and in the past. Further discussion will propose the future uses of airships for reconnaissance, surveillance and even extra planetary exploration. Based on these findings and the extensive literature review a modern airship concept will be theorized and modeled. The report will start by discussing in detail how the design choices for the different aspects of the proposed aircraft were made. Starting from setting up design specifics for a set mission criteria. Estimated weight and sizing of the proposed design will help establish design flow fro structural and stability analysis that follows. The report also contains a detailed discussion on aerodynamics of an airship and how it is different from fixed-wing aircraft. Care is taken when discussing the difficulties and sacrifices that led to these design choices. As the report progresses the proposed final design will start taking shape. Finally, a complete summary of finalized design and its viability are discussed. Followed by concluding remarks on the state of airships in today's aviation industry.

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1 INTRODUCTION

This report will investigate the conceptual design of a modern civilian transport airship. The key sections in this report are the motivation for this project, mission specifications, design approach, general layout of the airship followed by preliminary design calculations and discussion.

In the past before the advent of commercial airliners the airships were the way to travel transcontinental as well as between continents. There were many uses for these airships between the military and the commercial aspect. Unfortunately due to numerous accidents both from the military and civilian sector the age of airships soon faded away. Soon after the advent of commercial fixed-wing aircraft that were faster and safer than airships cemented its hold into aviation.

Recently, various institutions around the world are exploring airships as a viable alternative to fixed wing aircraft. Many companies have begun research for cargo transports, i.e. SkyLift, reconnaissance aircraft, i.e. Northrop Grumman's LEMV, or even a luxury aircraft such as the 'Aeroscraft' concept. All of these examples and more are discussed in detail under respective sections.

This project has two main goals. Firstly it aims to identify if there is a market need for this type of aircraft in the modern aviation and aerospace industry. Based on these findings and the extensive literature review a modern airship concept will be theorized and modeled. The report will discuss in detail how the design choices for the different aspects of the proposed aircraft were made. Care will be taken in discussing the difficulties and sacrifices that led to these design choices. As the report progresses the proposed final design will start taking shape. Finally, a complete summary of finalized design and concluding remarks are made on the state of airships in today's industry.

1 MOTIVATION & HYPOTHESIS

The airship industry at this moment is at very early stages in terms of passenger flights and military application. As of November 2014, there are no commercially operating passenger transport airships in the USA. The recent investments in the development of airships for the military and from private investors support this increased interest in airships (Clausen, 2012). The idea of luxurious air travel has existed since the birth of aviation and the need for more fuel-efficient aircraft are also a factor for this recent revival of interest. This alternative form of aircraft can also help address the problem of transporting large sized payload such as giant wind turbine blades from manufacturing site to offshore point of installation. Or even fly to remote places irrespective of terrain without the need for any runways.

These are the main reasons why plenty of recent airship prototypes are being shown off at various stages of development around the world (Tascona, 2013). However 'none' are currently operational that can provide insight or vouch for this technology. The key to success is to offer a modern airline passenger with large open spaces while being highly fuel-efficient, being able to stay in the air for weeks on end without refueling which can be a very tall order for conventional fixed wing aircrafts. But airships because of its lighter-than-air design have the potential to offer these spacious cabins to passengers and also be able to provide the space necessary for large-scale commercial cargo transportation. There is also a great opportunity for future growth and possibility of high profit margins by meeting this unmet demand and market monopoly. (Clausen, 2012)

Figure 1 Gondola arrangement in Zeppelin NT airship. (KG, 2011)

All current commercially operational airships are based in Europe, namely Germany and Switzerland. The companies are 'WDL Worldwide', 'Zeppelin NT' and 'Skycruise' in Switzerland respectively (Dziadecki, 2013).

All three of the service providers offer very similar gondola arrangement with large-open rectangular windows allowing the passenger to enjoy the view. These services lack the full amenities offered by conventional airliners. Given Europe is a top destination for tourists; this allows the flights to cover major destinations and landmark sites in their respective countries. So the question arises as to why there are no cruise airships operating in the USA.

The company with the most operating blimps in the US, which also offers passenger travel is 'Goodyear Blimps'; operated by Goodyear Corporation. The passengers are invitation only and the ride on offer is very primitive and similar to their European counterparts. (Goodyear, 2013)

Furthermore, in the USA, 'Airship Ventures Inc.' used to provide airship cruises for passengers right here in San Francisco, California. Unfortunately it ceased its operations from November 2012, due to high operating costs (VENTURES, 2012). This was a subsidiary of 'Zeppelin NT Inc.', which still operates in Germany as discussed earlier.

However there are several major players in the airship industry with promising prototypes that could be the future competitors. The figures 2-4 are the Aeroscraft, Samsung-Aircruise and the Strato Cruiser concepts respectively.

Figure 2 Aeros Aeroscraft ML-866 concept. (Tascona, 2013)

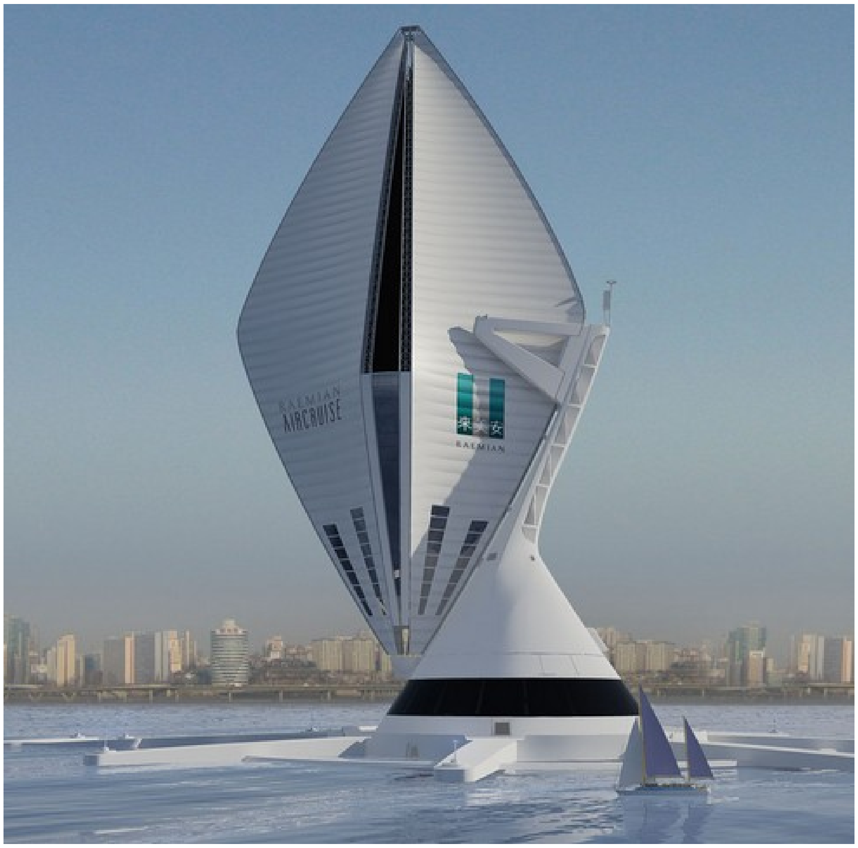


Figure 3 Samsung's Aircruise concept. (Tascona, 2013)

Figure 4 German, "Strato Cruiser" concept, showing lush interiors and amenities. (Tascona, 2013)

All three of the aircrafts mentioned above are designed and built with luxury of the passenger in mind. With services varying from full day spas to business areas fit to run an enterprise. Everything from fine dining and bedrooms with king size beds. (Tascona, 2013) There are however a number of airships that have been developed by the military that could serve as a platform for future passenger airships. 'Long endurance multi-intelligence vehicles' such as the recently developed P-791 Hybrid Airship design can be modified to accommodate up to 300 passengers (shown below). (Clausen, 2012). The figure shows how the airship could be used as a mobile command center operating for as long as 21-days without refueling ideally hovering over a specific area. Additionally this airship has unique landing gear that allows it to land on any terrain, even water. This kind of capability is impossible to achieve with fixed wing aircraft.

Figure 5 P-791 from Lockheed Martin LEMV prototype. (Clausen, 2012)

These findings have helped identify a niche in novel airship uses that has yet to be tapped into. With so many companies coming into the airship industry over the last decade with radical concepts it only helps fuel customer interest for alternative form of air travel and commercial transport opportunities.

At this point it should be noted that all these examples mentioned so far are still either in prototype phase or test-flight states with very little available data that can be used for design verification for this analysis. Therefore the following analysis will focus on both historical and present designs for comparison and design validation.

2 LITERATURE REVIEW/ BACKGROUND

Airships were first introduced to the world by an Italian mathematician in the 1670‟s, however it took a Frenchman in 1844 to finally build one (Collins, 2009). First airships were known for luxury trans-Atlantic travel. Depending on shape and internal structure lighter-than-air aircraft has many names such as dirigibles, zeppelins and blimps. After its introduction to the masses in the early 1900s, it was thought to revolutionize air travel. However, its troubled history, which includes several catastrophic disasters have led to very few modern day outings in the passenger aircraft and the military sector.

The key challenges facing the development of airships today are cost, controllability and safety. The cost aspect includes development costs, including production. Figuring out a way to fully control an airship is another area significant research. This is understandable since the whole aircraft is essentially a fortified and augmented balloon, which can be hard to control in high gusts. Finally the idea of safety is one that carries a negative bias due to airship's history. However, modern control techniques and material technologies can tackle key safety problems. Though early 19th century airships only cruised at several thousand feet above sea-level, modern airships can be designed to cruise at 12,000 feet or higher (Dietl 2011). The lower limit of cruise can pose a hazard for flight over cities and other landscapes. Alternatively higher altitudes present safety and controllability issues. It can be seen that there are many challenges that needs to be addressed before a truly modern airship becomes a reality.

Besides all the challenges outlined above, both the military and the civilian sector has shown significant interest in the development of airships. The military proposed to use an airship as a multipurpose reconnaissance aircraft (Clausen, 2012). The science community is looking into possible airships to be used to explore other planets such as Mars (Coleman, 2006). The civilian sector has shown off airship concepts promising future luxury air travel (Tascona, 2010). Airships the sizes of cargo ships to replace container ships are also being looked into. Modern day technologies and deep understanding of lighter-than-air aircraft can make the ideas mentioned above a reality.

3.1 Challenges and possible solutions

Cost of developing a new aircraft can be in the millions. The development of a lighter-than-air airship is no different. Considering the lifting-gas alone to be Helium the price reach astronomical numbers. This is due to Helium being very expensive to source. An example would be a 600ft long, 2-million ft^3 capacity airship costing $186 million to fill (Plumer, 2013). However, this is just a one-time cost with occasional top-ups to compensate for leaks. There are two immediate solutions to this problem.

Figure 6 COSH system in an Aeroscraft concept. (Aeros, 2012)

One solution is the COSH system developed by Aeroscraft shown above, which re-pressurizes the helium into tanks rather than siphoning it out to control buoyancy (Aeros, 2012). This means the airship will not need a full refill of helium after every flight. Second possible solution could be to use Hydrogen as the lifting-gas rather than helium. Hydrogen is flammable and is believed to be the root of Hindenburg's demise. Hydrogen is cheap and can be easily sourced, unlike Helium. However, it could be safely contained in a modern airship with advanced lightweight fire retardant fabric materials.

Cost of the lifting-gas aside the manufacturing of such an aircraft is also very high. Since airships are being developed from the ground-up there is no existing infrastructure to help alleviate the costs of the production process. These include research into new materials, engines and also control systems. New designs might need new production methods, which might be costly.

The advent of 3D printing of plastics and metals can be one solution to the complex production methods involved in airship construction. However 3D metal printing still remains very expensive and printing a 600-feet airship structure would be financially impractical at the moment. Research has led to a company from London that is planning to print 3D houses that uses significantly less material compared to conventional houses. This is achieved by printing using an algorithm that mimics the inside of a human bone (Barre, 2012). The algorithm allows the structure to be optimized for the specific load condition and use the least amount of material. The image in Figure 2 below shows a concept of such a design.

Figure 7 3D printed house concept using SoftKill algorithm. (Barre, 2012)

It can be seen from the figure above that this technology could be used to create a very light and strong "gondola" for an airship. This algorithm could also be implemented to construct the main internal structure of the airship. Depending on the size and specifications of the airship the material used can be adjusted in terms of type and composition. Anything from metal alloys to metal-polycarbonate hybrids could be utilized for this purpose. 3D printing is very promising in terms of future manufacturing, but the technology is still at its infancy in terms of mass scale production.

Another major challenge to airships is controllability. Early airships were known to fly low and only in good weather due to controllability limitations. Even the Hindenburg cruised at 650ft to stay below clouds and avoid high winds (Collins, 2009). A flight altitude of 650 feet is not feasible in modern populated areas. Additionally, high altitudes present high-speed gusts, which present a problem for large airships. This can be addressed by implementing intelligently placed vectored thrust system along with efficient control surfaces. The Aeroscraft used vectored thrust to not only compensate for the smaller control surfaces but also to gain increased stability and control (Aeros, 2012). Together with fly-by-light control systems, these innovations will improve the handling and ride quality of future airships. Good news for future pilots and passengers.

Airships do not have the best track record when it comes to safety. However, the same safety precautions may not apply to modern airships with modern materials and autopilot systems. It should be noted that early airships navigated the seas with a map and a compass (Collins, 2009). At this point it can be argued that technologies such as smart 3D printing, light-weight materials, vectored thrust and fly-by-light systems can be combined to create a very safe and practical airship.

3.2 Possible applications

US Air Force is looking into long-endurance multi-intelligence vehicles‟, which are airships that can replace fixed-wing aircraft for extended surveillance missions (Clausen, 2012). The proposed airship is called Blue Devil 2‟ and received $86 million in funding and is to be deployed in Afghanistan by Northrop Grumman. The military is starting to consider the benefits of using airships for surveillance, since the airship does not require any fuel to maintain cruise altitude. This will allow the airship to stay up in the air for periods up to 3 weeks. All the while, it can relay multiple signals from satellites overhead, ground units and installations and even between other aircraft in its airspace. Figure below shows the implementation of one such airship. The airship is planned to serve as a remote command post with its own data center and reconnaissance equipment.

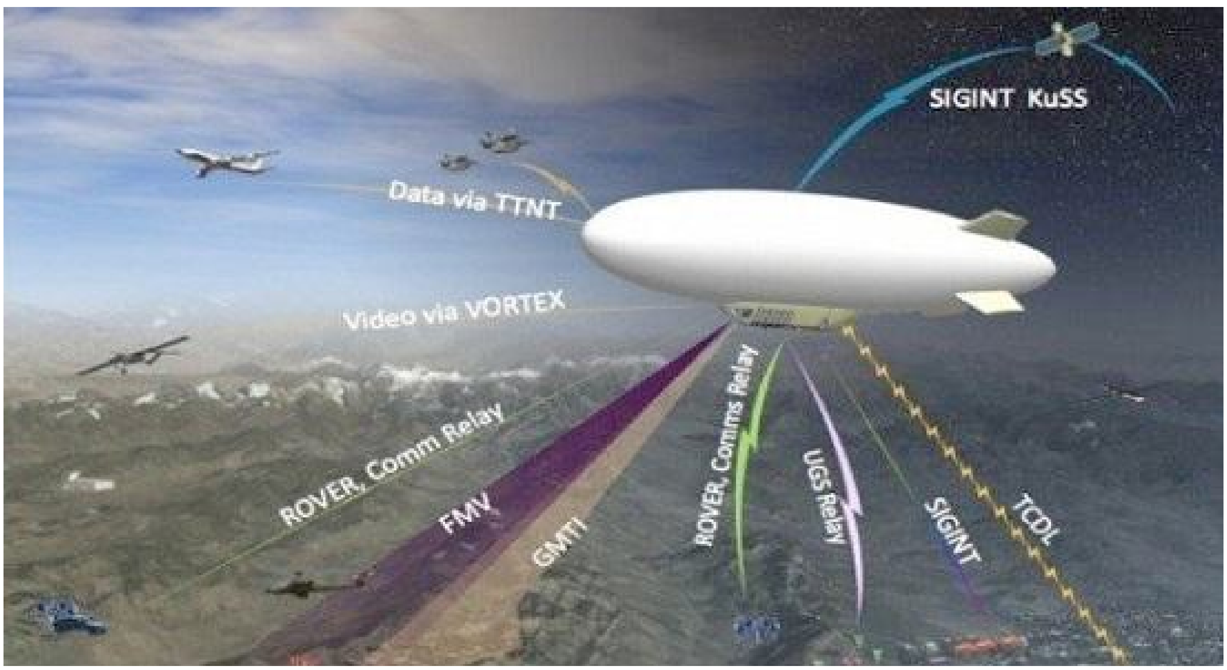


Figure 8 Long-Endurance Multi-Intelligence Vehicles or LEMV. (Clausen, 2012)

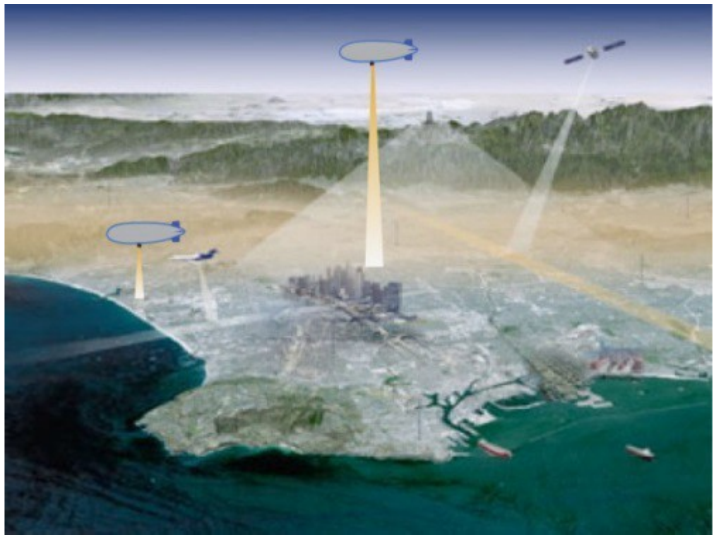


Figure 9 'Megacities' concept utilizing high- and low-altitude airships to compliment ground-based communications (Keck, 2014)

Similarly, a mobile data-center could provide Internet or cellular access to remote or inaccessible areas. The recent typhoon to hit the Philippines damaging its infrastructure is one example where one such airship could be implemented to support aid relief workers by allowing them to stay connected and share vital information about survivors and facilitate the distribution of essential aids. This can also work for providing Wi-Fi connection to a fair-ground outside of cellular or Internet coverage. Another use could be the secure monitoring of drones of the future, over an area. Future companies may wish to do deliveries via drones, as announced recently by Amazon‟ (Gross, 2013). Since these drones may be prone to hacking and other damages, a mobile secure off-the-grid control network might be beneficial. Additionally airship surveillance over populated areas can be a „greener‟ alternative to police-choppers, since helicopters use more fuel and make significantly more noise to operate.

3.3 Stratospheric Airship concepts

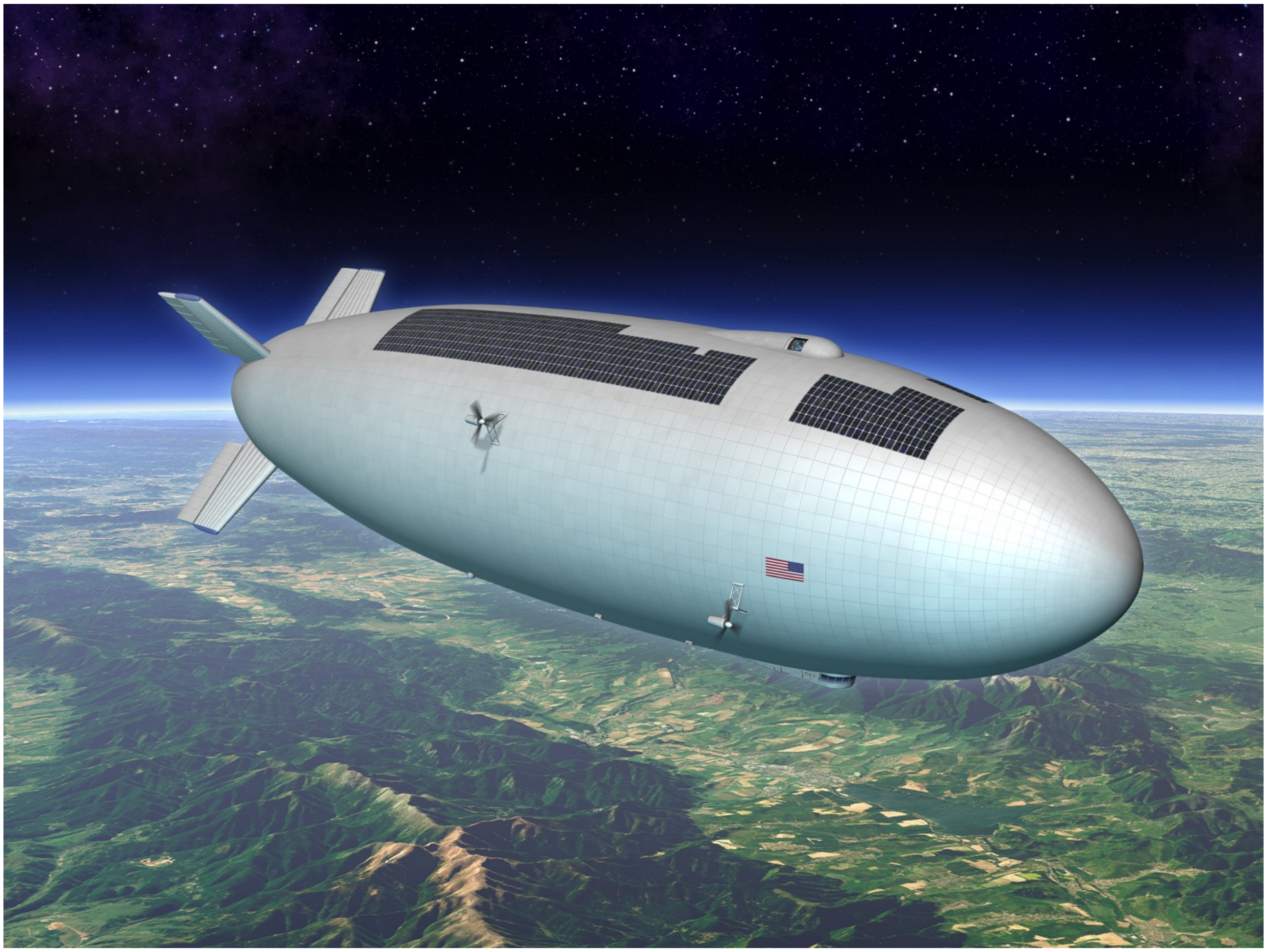


Figure 10 Airship observatory concept. (Keck, 2014)

Illustration of an airship observatory concept, including a world-class telescope mounted on the top of the airship and a suite of Earth and atmospheric instruments mounted on the bottom. Mike Hughes (Eagle Interactive) / Keck Institute for Space Studies

Airships represent an exciting complement and alternative to expensive geosynchronous earth orbiting (GEO) satellites or constellations of low earth orbit (LEO) satellites. A stable platform positioned in the lower or middle stratosphere (60-90 kft) would provide a space-like observation outpost far more accessible and less expensive than GEO or LEO platforms. Given an increasing number of well-motivated scientific satellite missions in the last three decades, there are strong drivers for the use of relatively inexpensive LTA vehicles for a wide range of Earth and space applications.

In particular for Earth science, the capabilities of stratospheric LTA platforms could be complementary to that of spacecraft (Smith and Rainwater 2003). While LEO satellites have proven to be extremely effective at capturing large-scale context, they do not provide persistent observations of specific localities or regions owing to their rapid orbital traverses.

As a complement to LEO satellites, GEO satellites obtain continuous observations of specific regions but typically at the expense of degraded spatial resolution. Neither GEO nor sun synchronous LEO satellites can capture diurnal behavior of targeted phenomena. Also, given their higher cost and complexity, relatively few satellites are launched per year. The low replenishment rate of NASA Earth satellites has been particularly acute over the past decade, with the present set of environmental satellites operating well beyond their design life, placing the system as a whole in danger of collapse (NRC, 2007 - Earth). These satellite systems cost on the order of 1 billion USD (10-100 times the cost of airships) and typically conduct specifically designed experiments on non-reusable platforms.

3.4 Identifying unique platform capabilities

Recognizing the need for critical and affordable observations that span the range of Earth processes, the National Global Change Research Plan (USGCRP, 2012) seeks to "sustain and strengthen the capacity to observe long-term changes in the global Earth system and integrate observations to improve fundamental understanding of the complex causes and consequences of global change". As part of that capacity, the NRC finds that alternative platforms, such as balloons and aerial vehicles, offer flexibility and may be employed, in some cases, to lower the cost, relative to satellites, of meeting science objectives (NRC, 2012).

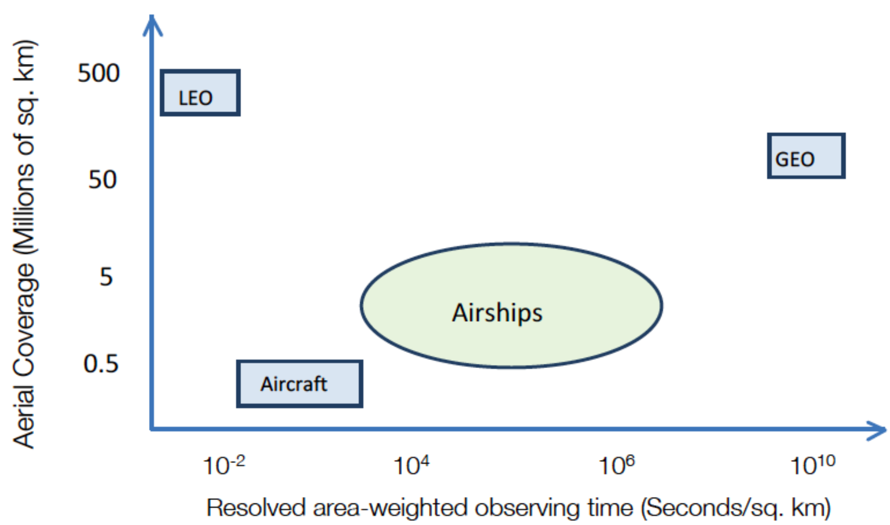


Figure 11 Comparison of observational attributes of airships to other platforms. (Keck, 2014)

Four regimes of Earth science measurement attributes: airship (high spatial and temporal resolution, diurnal to seasonal temporal coverage, local to regional spatial coverage), conventional fixed-wing aircraft (high spatial resolution, low temporal resolution, seasonal to inter annual temporal coverage, regional to continental spatial coverage), LEO satellites (moderate spatial resolution, low temporal resolution, weekly to inter annual temporal coverage, global spatial coverage), GEO satellites (low spatial resolution, high temporal resolution, diurnal to inter annual temporal coverage, continental to third-o- sphere spatial coverage).

Surveillance aside, airships can be used by passengers for travel. Civilian airship sector has seen a significant investment in the development of luxury airships. Concept airships such as the Aeroscraft, Strato Cruiser or even the Manned Cloud‟ are all examples of how the private sector is trying to revitalize the age-old concept (Tascona, 2010). Except a prototype from Aeroscraft, all other airships mentioned are still in the concept stage. The luxuries promised by these aircraft are not far from the luxuries enjoyed by mid-1800s Parisians on board the massive airships of the past. However, not all airships are several hundred feet behemoths.

3.5 Comparison study of modern airships

Mission	Operating Altitude	Airship Type and Examples (1st Flight)	Altitude (Feet)	Endurance or Range	Status of Technology	Characteristics
Intelligence, Surveillance, & Reconnaissance	Low Altitude	Conventional BD2 (2012) MZ-3A (2006)	Up to about 20,000	100 to 300 hours	One system currently operating; Others under con-struction	Relatively mature technology
		Hybrid LEMV (2012)	Up to about 20,000	500 hours	Technology demon-strations ongoing	Uses static lift from helium, aerodynamic lift from the shape of the envelope, and vectored thrust to stay aloft
	High Altitude	Conventional HALE-D (2011) HiSentinel (2005) ISIS (2010)	65,000 to 75,000	Greater than 400 hours	Technology demon-strations ongoing	Very large envelope volume to sustain lift
		Payload-Return Star Light (N/A)	65,000 to 75,000	100 to 300 hours	Technology demon-strations ongoing	Payload is detachable and returns to the point of origin; airship is single-use

Based on Exhibit 3 of the Congressional Budget Office’s 2011 report: “Recent Development Efforts for Military Airships." This table shows the various airship classifications recently and currently under examination under various DoD programs. Several examples are also shown. More information is given in the following section.

BD2

The Blue Devil 2 airship, built by Mav6, is a conventional non-rigid designed to fly at 20 kft for 4 to 5 days with a 2,500 lb ISR payload including onboard processing that makes it an aerial data fusion node. Originally scheduled for first flight in the fall of 2011, the program was cancelled in June 2012 due to technical and programmatic challenges.

MZ-3A

The Navy's MZ-3A, a modified American Blimp Corporation A-170 commercial airship, is a 178 ft long non-rigid ISR airship that carries a crew. It is currently the only operational airship in the DoD and is used for payload test and evaluation. It was used recently to monitor the Deepwater Horizon oil spill in the Gulf of Mexico. The MZ-3A is a platform for up to 2,500 lb of cameras, radar and other sensors. It flies at up to 9.5 kft and cruises at 40 mph. Its typical flight duration is 10 hours but it has a 24-hour capability.

LEMV

The LEMV is a non-rigid airship of hybrid design. It was developed for deployment in Afghanistan in 2012. It can operate at 20 kft for up to 21 days and can produce up to 16 kW of electrical power and carry a 2,500 lb ISR payload. Schedule delays and weight growth reduced the altitude to 16-kft and flight duration to 16 days by the time the first flight was performed in August 2012. The program was cancelled in February of 2013 and the vehicle was deflated and sold back to its builder, Hybrid Air Vehicles (HAV) in October 2013.

HiSentinel

The HiSentinel program is a family of high altitude airships to provide persistent communications and ISR capability to the DoD. The HiSentinel program was a tactical airship demonstration program for the DoD to demonstrate the various key technologies for a stratospheric airship. The HiSentinel systems were comprised of the airship, ground support systems, weather support system, and flight/payload command, control and communications ground station. Six high altitude airship-engineering flights have been conducted over the years with five of those flights achieving greater than 65 kft altitudes. All key stratospheric airship technologies were demonstrated during the development program.

HALE-D

The HALE-D is a high altitude conventional non-rigid airship demonstrator for the HAA, the larger High Altitude Airship. Intended to operate at 60 kft for two to three weeks with a small demonstration payload, the first flight occurred in July 2011. Unfortunately a problem occurred during ascent and the flight was terminated after rising to only 32 kft. The airship came down in a heavily wooded area of southeastern Pennsylvania. During recovery operations, the hull caught fire and was destroyed. Funding for the program ended in 2011.

ISIS

The ISIS (Integrated Sensor Is Structure) Demonstration System Program is a conventional non-rigid airship that includes an integrated Radar system. The airship is 511 feet in length and operates at an altitude of 65 kft for one year. Originally intended

For a first flight beginning in late 2012, cost and technical challenges have caused the program to delay airframe development and to refocus on radar risk reduction testing, which will complete in mid-2014.

Star Light

The U.S. Navy's Naval Air Warfare Center awarded a Phase 1 and Phase 2 contract to begin development of a next generation stratospheric airship with a radically new design. The vehicle, named StarLight, was proposed to deliver unprecedented performance in operating altitude, flight duration and forward velocity. The uniquely designed vehicle would supposedly operate at 85 kft above the earth's surface powered solely by photovolatics. Current status appears to be inactive.

Figure 12 on the following page shows the relative sizes of various airships. The comparison includes both modern and historical airships. It will become apparent that the proposed future designs are in excess of 600 ft long. The ISR capabilities represented by such a platform could be highly beneficial for both civilian and military use. However, the proposed design discussed later in this paper is closer to LEMV in terms of size and structure.

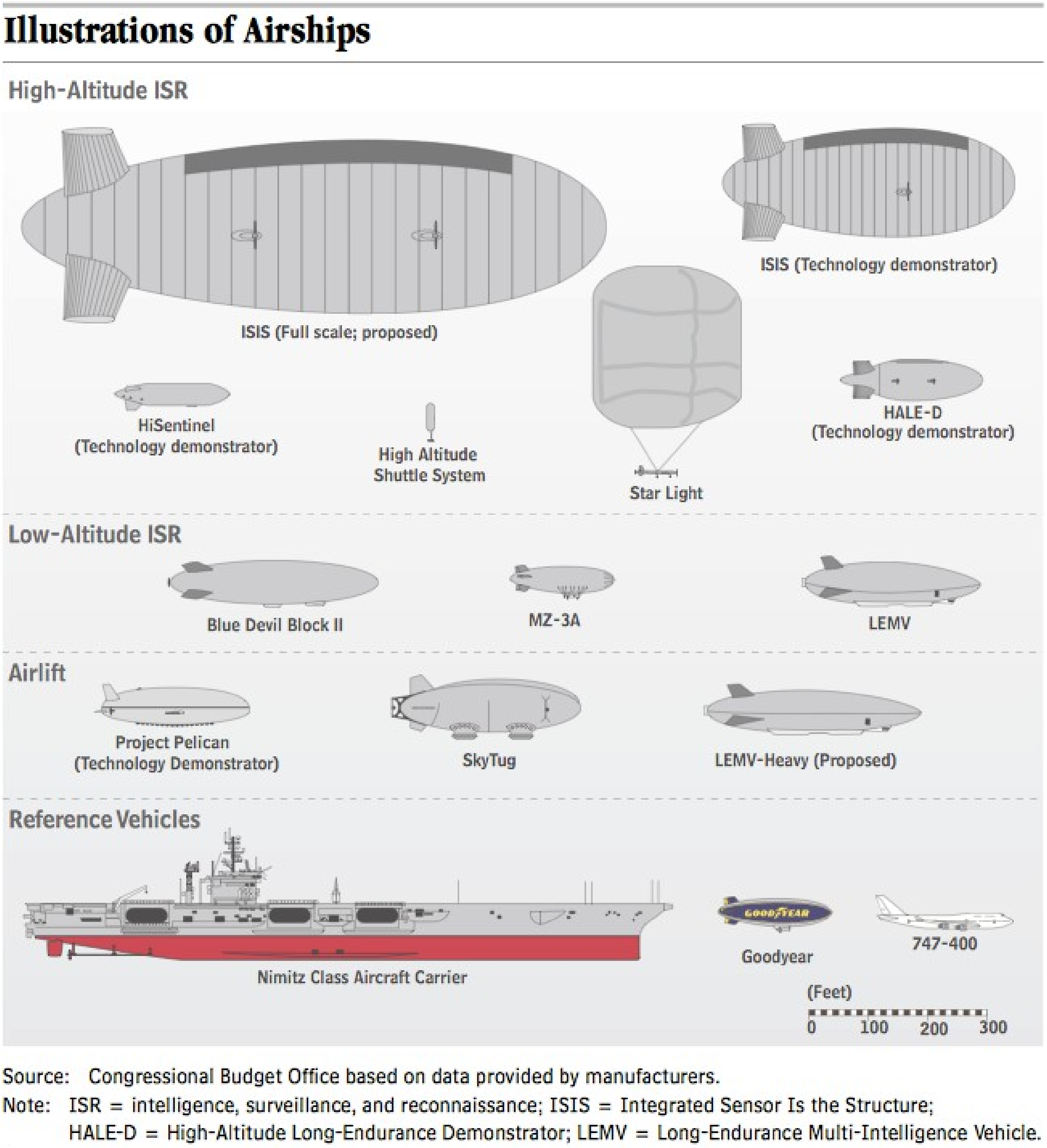


Figure 12 Size comparison of relative airship designs (Keck, 2014)

Lighter-than-air aircraft can be used as a micro-aerial-vehicle as well. All the recent advances in miniaturization of electrical components can be utilized to create lighter-than-air MAVs. Researchers even went as far as to create ornithoptic‟ blimps for indoors use using flapping propulsion to fly around (Dietl, 2011). A toy version of this concept is being marketed as a children's toy. Figure 4 below, illustrates the interesting contraption.

3.6 Further applications of the airship platform

Figure 13 AirSwimmer aptly titled airship toy. (Dietl, 2011)

The AirSwimmer, like the name suggest is a lighter-than-air aircraft that moves by flapping its tail for thrust. Changing the cg position by moving a small-motorized weight does the control of pitch. This is a very simple concept that can be utilized for indoor use, especially for warehouse inventory or shopping-mall/indoor-venue surveillance. Though, these concepts are limited to indoor use, research is being done that are completely out of this world.

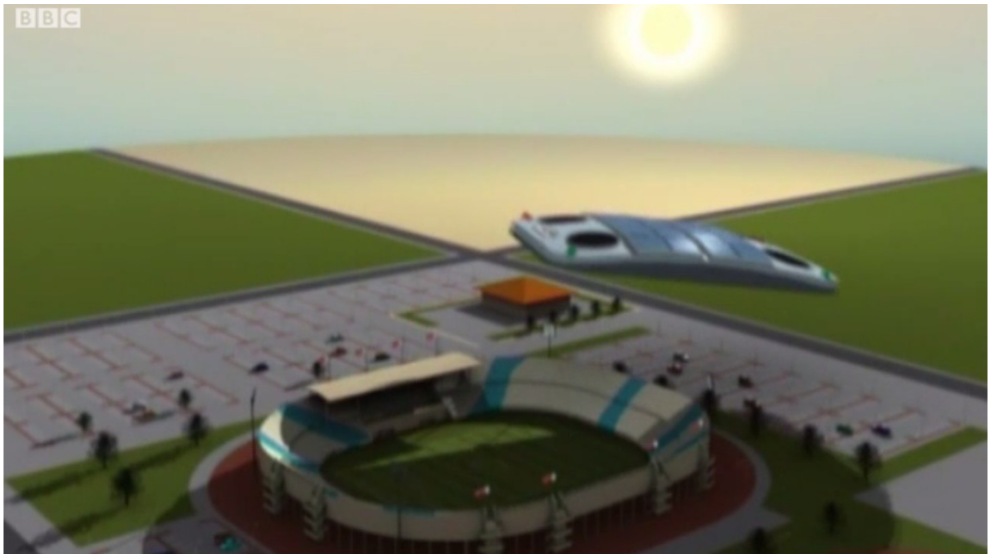


Figure 14 Qatar's "Robotic Cloud" concept for FIFA 2022. (Dietl, 2011)

A journal titled "The use of a blimp to investigate life on another planet such as Mars or Titan" explains the benefits of using a blimp rather than a rover or a fixed wing aircraft for planet exploration. The team behind this research argued that an „airship‟ would be easier to transport and operate on other planet's atmosphere (Coleman, 2006). The use of propellers and engines can be avoided completely by using flapping propulsion. This is very similar to the toys mentioned earlier. They pointed out that, it would be more feasible than sending any other form of exploration vehicle to Mars or Titan. This is because it can be transported deflated and there are no wings or engines involved.

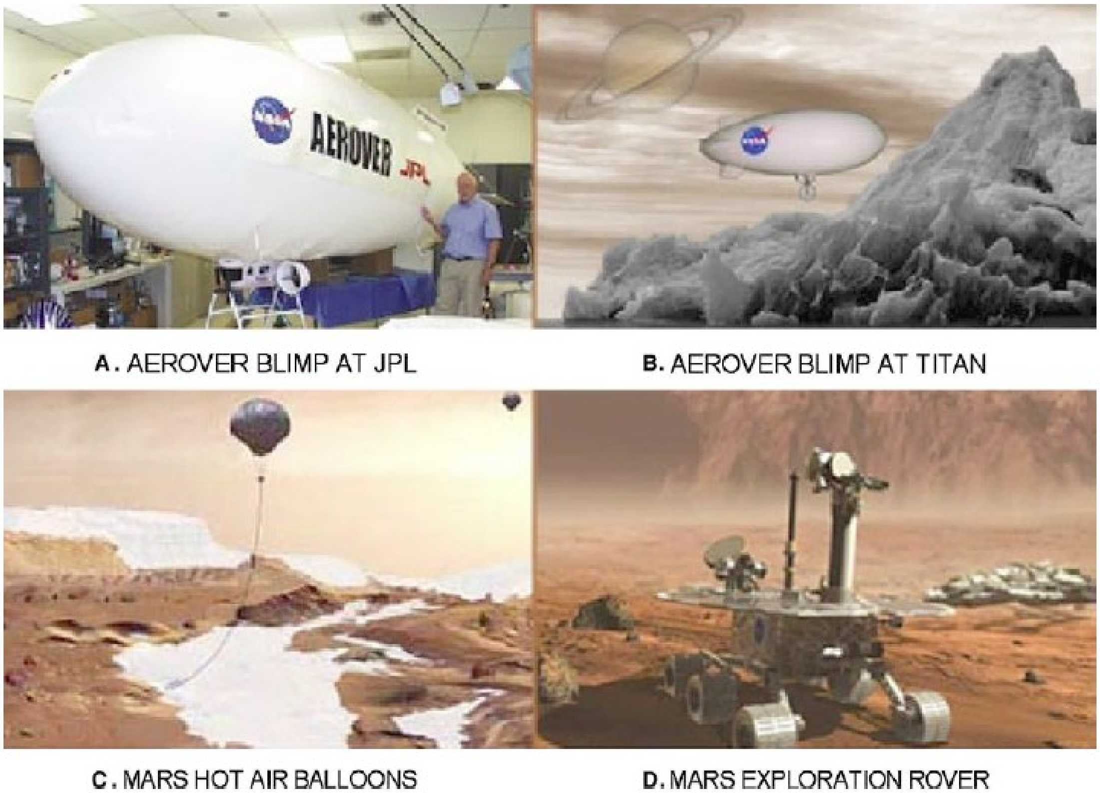


Figure 15 Airship concepts for planetary exploration. (Coleman, 2006)

Additionally, lighter-than-air UAVs could be used to monitor geographical changes on Earth. The idea of identifying sediment sources using a blimp was first published by (Marzolff, 1997); they highlighted the use of blimps as a cost effective and adaptive method of monitoring areas through large-scale aerial photography. Applications can range from rainforests/wildlife preservation to the study of river sedimentation over time.

3 MISSION SPECIFICATION & METHODOLOGY

Since this new method travel needed to provide amenities and services that made it unique from conventional fixed wing aircraft for market viability. An emphasis was given on providing luxury and first-class experience during flight such as most of the commercial examples cited earlier.

- **Range – 1500 NM**
- **Payload – 11760 lbs**
- **Service Ceiling – 12,000 ft**
- **Climb/Descent – 300 ft/min or 100 ft/min (one engine inoperable)**
- **Cruise Speed – 50 knots**
- **Max Speed – 120 knots**

4.1 Range

The range needs to be sufficient to handle the full load of passengers and their luggage, as well as the personnel that will be on board to handle the day to day tasks of cooking, cleaning and flying. Due to the nature of the airship the ability to be variably buoyant means that if it takes an extended amount of time to land the use of the fuel will be minimized to just hold in the same position. A total range of 3,100 nautical miles should be sufficient for any unforeseen case.

4.2 Useful Load and Payload

The proposed payload consists of the thirty passengers, 100 lbs baggage each passenger, ten (10) crew members, and 100 lbs baggage per crewmember. In 2009 the European Aviation Safety Agency (EASA) conducted a study and found that the standard assumption for mass per person on an aircraft has increased to 88 kg or 194 lbs per person. This standard mass includes carryon luggage and any infant under the age of 2 years old. This was used for the total payload calculations. Using this the total payload capacity is calculated to be 11760 lbs.

4.3 Service Ceiling

With transcontinental flights in mind the airship will need to have a service ceiling of 12,000 ft. This service ceiling will be helpful in deciding the trajectory of the flight and also allow for many different options for the flights offered. This will also mean that there is no need for oxygen supply in the cabin.

4.4 Climb and Descent

Based on the TAR requirements in the transport airship requirements document the airship shall have no less than 300 ft/min climb rate with all engines operable and no less that 100 ft/min with one engine inoperable. (Blenk-Strasse, 2000)

4.5 Speed

The use of a luxury airship to be transcontinental will need to be able to cross the U.S. within a given amount of time. Thus it was decided that traveling across country in about 2 days allows for a round trip of close to a week with off time at the destination. This means that a flight speed of about 50 knots. The capability of completing the flight faster can be of use in different situations so a maximum speed of 120 knots will allow for a transcontinental flight in about 19 hours; New York to London journey with a distance of 3,020 nautical miles.

4.6 Comparison study of proposed Design

Table 1 Proposed design specifics compared to similar airships.

Name	Design	LZ 127 Graf Zeppelin (1928-37)	LZ 129 Hindenburg (1931-36)	GZ-20A (1969)	Voyager	SkyCat 20	Aeroscraft ML866
Type	Transport	Transport	Transport	Transport	Transport	Transport	Transport
Manufacturer	NA	Zeppelin	Zeppelin	Goodyear	21st Century Airships Team Inc.	World SkyCat ltd.	Worldwide Aeros Corporation
Length (ft)	300	776	804	192	223	266	210
Diameter (ft)	110	100	135	50	190	134.5	118
Height (ft)	110	100	135	59.5	125.6	72	56
Volume (ft^3) 10^6	1.901	3.707	7.062	0.2027	0.532	1.1	1.388
Weight (tons)	36.25	95	255.75	6.42	not found	58.6	not found
Speed (mph)	57	72	76	50	not found	85	138
Range (miles)	1500	4900	4560	not found	not found	2700	3100
Altitude (ft)	12000	650 (max 6000)	650	1000-3000 (max 10,000)	not found	9000	5000
PAX	30 + 10 crew	20 +36 crew	72 +40crew	6 +1pilot	19 +2 pilots	70	not found

The comparison shown on Table-1 provides a clear image of size and weight to historical airships. It should be noted that most historical airships namely the Hindenburg was 800ft long and 135 ft in diameter. The more conservative approach to this design is noticed in modern airships, in terms of sheer size. However, the operating altitude of the modern and the proposed airship is much higher at 5000ft and above compared to just 650 ft of the historical ones. This comparison will aid the process of effective weight and size estimations of the proposed airship.

4 WEIGHT & SIZING

The total weight of the airship was obtained to be 54,000lb using CATIA design. The figures below show the two floor designs along with cabin layout. Table 2 below shows the various components of the airship and their masses.

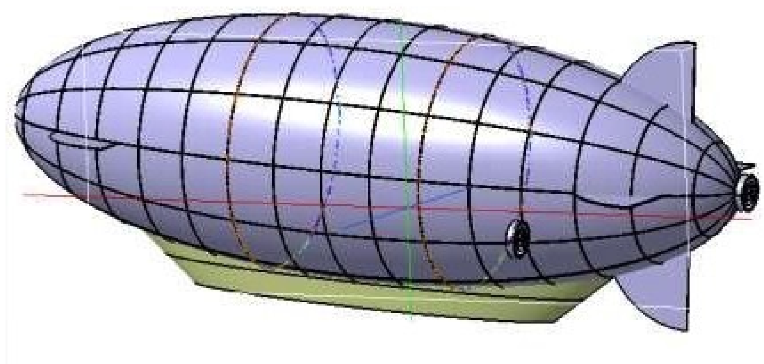


Figure 16 full-proposed airship structures

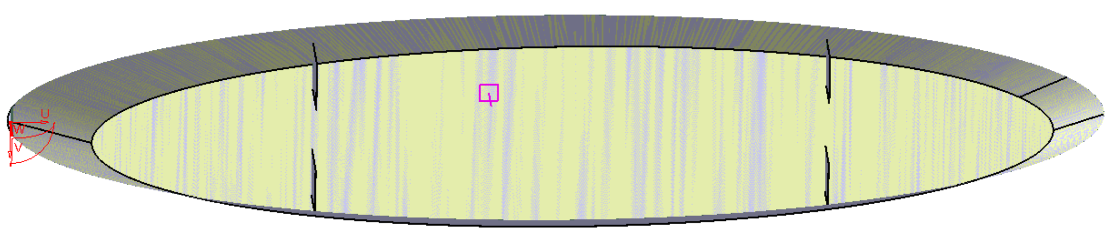


Figure 17 Proposed lower deck layout

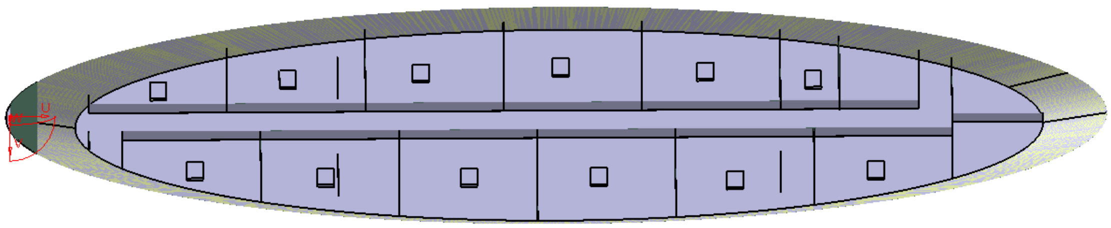


Figure 18 Proposed upper deck and cabin layout

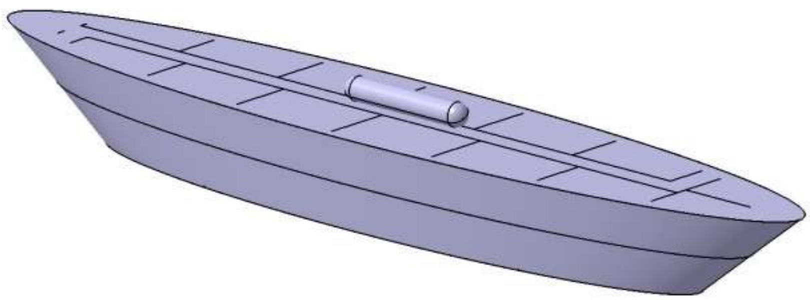


Figure 19 Preliminary hull design, indicating fuel tank position and relative size.

Table 2 Detailed breakdown of proposed airship weight

Structure	Weight (lb)
1st floor:	2206
Tables	180
Sitting arrangement	200
Lounge	250
Equipment	250
Public bathroom	300
2nd Floor:	3003
Flight Instrumentations	100
Rooms furniture	1500
Rooms bathroom	1100
Equipment	200
Roof	3922
Outer envelop	4963
1st floor walls	192
2nd floor walls	2741
Supplies	350
Food	250

Beverage	120
Lighting systems	60
Water	5000
Water filtration system	250
Electric system	400
Engines	810
Cabin	27000
Gas Tank	550
Structure	20,000
Empty Weight	47,500
Fuel Weight	13,020
Payload Weight	12,000
T/O Gross Weight	**72,547**

5 STRUCTURAL CONCEPTS

6.1 Internal Structure Design

The preliminary design of the structure will mimic the original zeppelin style of dirigible as a rigid airship. The material chosen to be used is a plain weave carbon-fiber epoxy that has a density of $0.056 lb/in^3$. This was chosen due to its excellent mass properties as well as its excellent longitudinal and transverse material properties. There will be 12 longerons running the length of the airship 30° apart as to make a circular cross-section, and a central internal structure that will attach to the cabin. The internal structure is a truss system that will increase the strength of the total system where the cabin will be attached and be a primary load bearing structure. The engines will be attached at a section where there are structural supports in the center as well as in the rear where the longerons attach together. Shown in the figures 20 and 21 below.

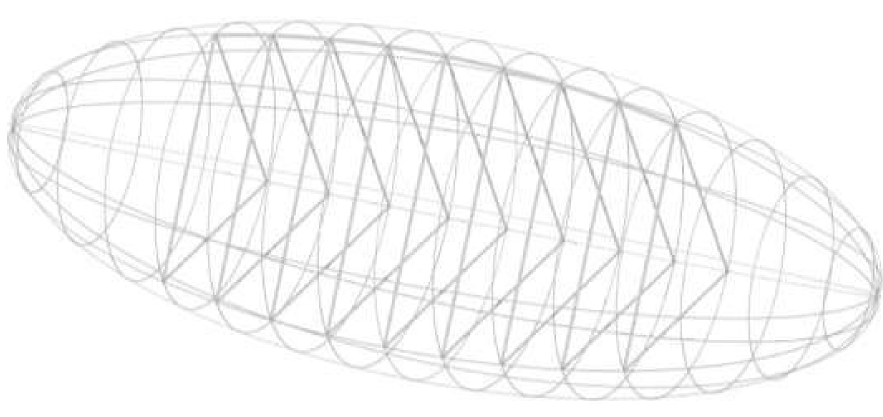


Figure 20 Primary Internal Structures

The stabilizers will also be attached to this structure seen above. The internal supports seen from the primary internal structure are 20ft apart and are only forward and aft of the Cg to provide extra support for the hull attachment and withstand the mass of the cabin. The cross-section view below provides a better view of the oval longerons and support structure.

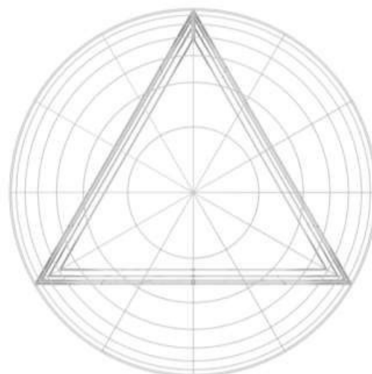


Figure 21 Cross-section view of the internal structure

This structure can then be used for complete structural analysis to find deflections and stresses.

Figure 20 shows the cross sections of the ribs and attachment points for the longerons. The diameter changes from 110 ft to 39.49 ft from the center rib to the last rib closest to the nose. The useful total volume inside for the balloons and cabin to fill is about 1,901,000 ft^3. This is required due to the need for 1,101,000 ft^3 of helium needed for the entire system to be neutrally buoyant and at 12,000 ft the volume of helium increases to 1,762,000 ft^3. This allows for 139,000 ft^3 of extra space of added helium for lift if needed.

6.2 Structural Analysis

A structural analysis was completed on one of the middle portions of the entire structure due to faulty meshing that was occurring on larger models. The analysis included five (5) of the structural supports as to mimic the stress and deformation that will occur on the structure under loading. The Von-Mises stress analysis can be seen in Figure 22.

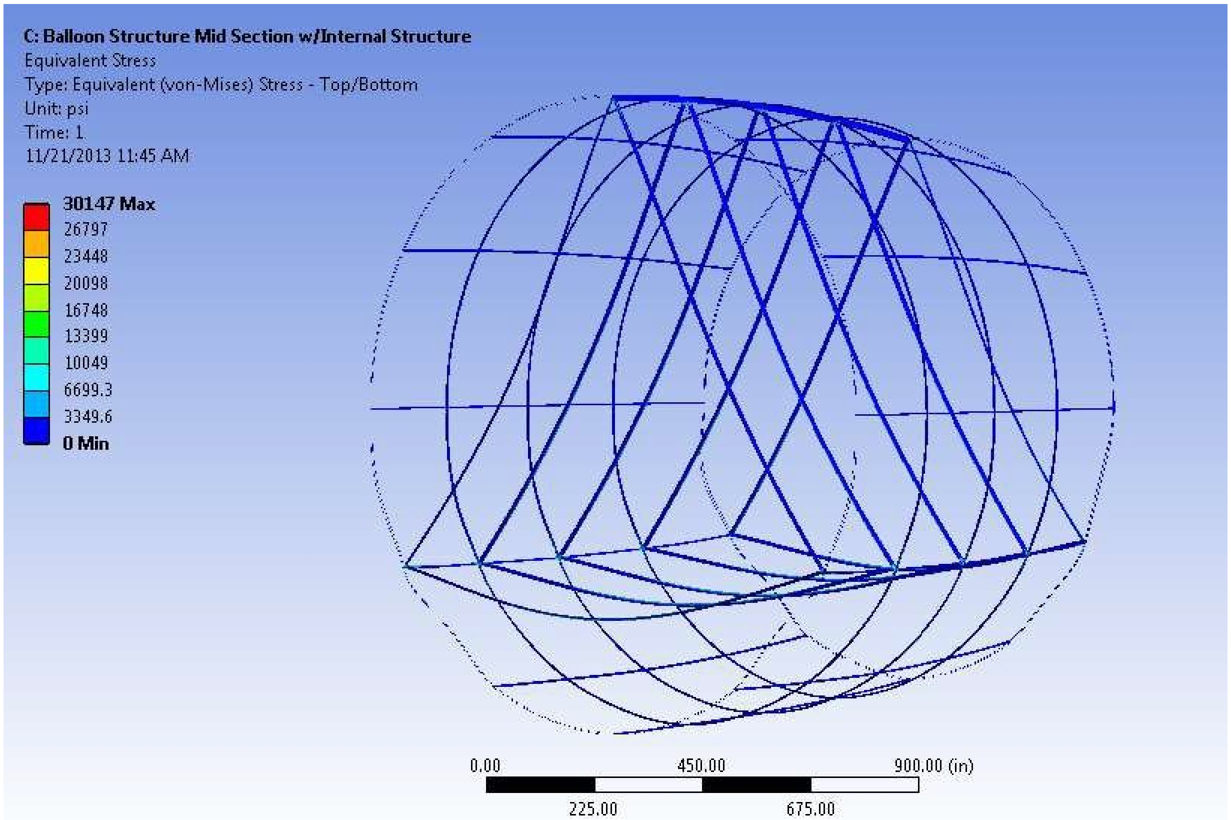


Figure 22 Structural stress analysis with cabin mass

As seen in Figure 22, the Von-Mises stress occurs at a maximum of 30147 psi. This is significantly less than the ultimate strength of carbon-fiber epoxy at 91,000 psi**.** This allows for a factor of safety of 3.02. This factor of safety is allowable for the design.

The total deformation can be seen in Figure 23. This shows the deformation that is occurring under loading.

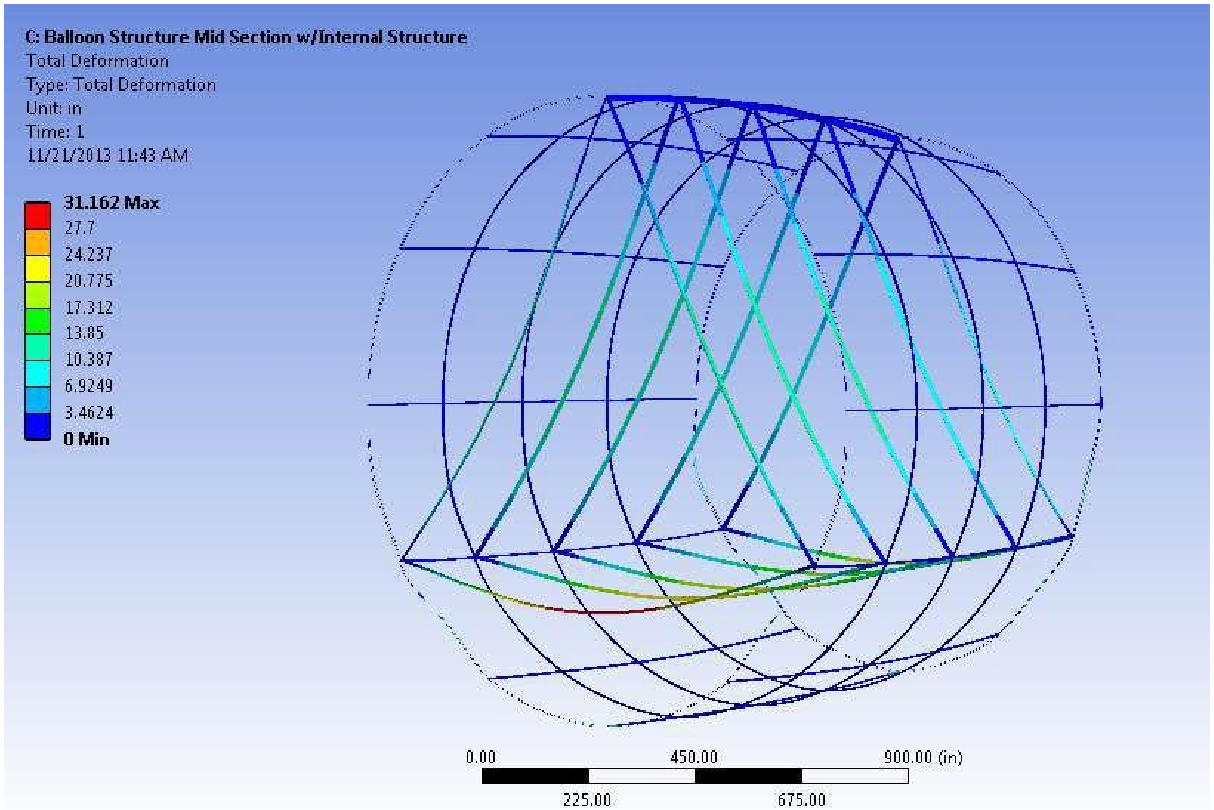


Figure 23 Structural Deformation analysis with cabin mass

Figure 22 depicts the total deformation that is occurring under a loading of 1g and 1700 lb per beam. From the figure it can be seen that the total deformation is 31.162 inches the internal structure. The highest deformation occurs on the front support. This is due to the fact that the triangular piece was cut in half so the support of the triangle is removed. This deformation should react like the other beams to be around 20-24 inches. When the tensioning lines are added this deformation will decrease. Unfortunately they could not be modeled with this program without it failing to mesh. It can be seen that the deformation occurs mainly on the internal structure and the external structure has minimal deformation occurring.

A lateral analysis was completed on the structure as to determine the stress and deformation that would occur under a gust. This requirement is given in the TAR as a gust of 25ft/s. Using Bernoulli's equation the pressure at the stagnation point is determined to be 10.73 psi. This is used due to the ease of analysis. The lateral stress can be seen in figure 24.

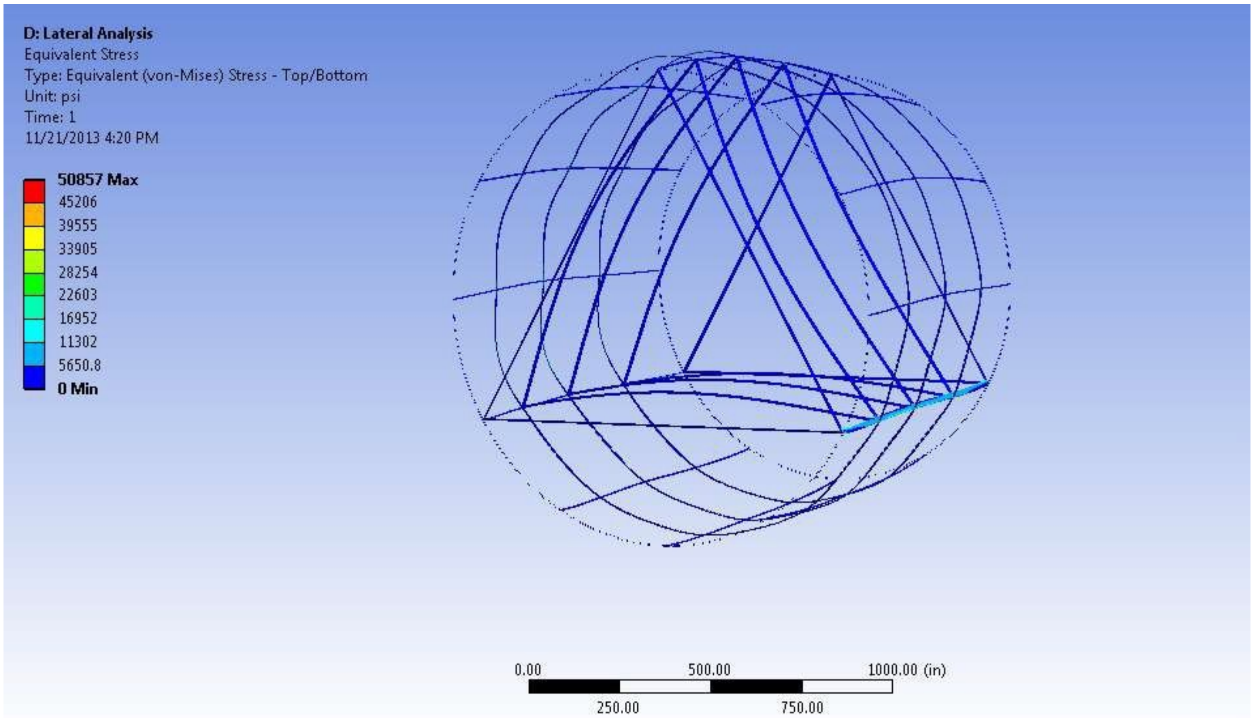


Figure 24 structural stress analyses with lateral gusts

Depicted in figure 25 the maximum stress with a gust of 25 ft/s is 50857 psi. This calculates to a factor of safety of only 1.79. The stress will decrease with added tensioners across the center of the circular cross-section, which will increase the factor of safety. Due to the lack of computing power the analysis could not be completed.

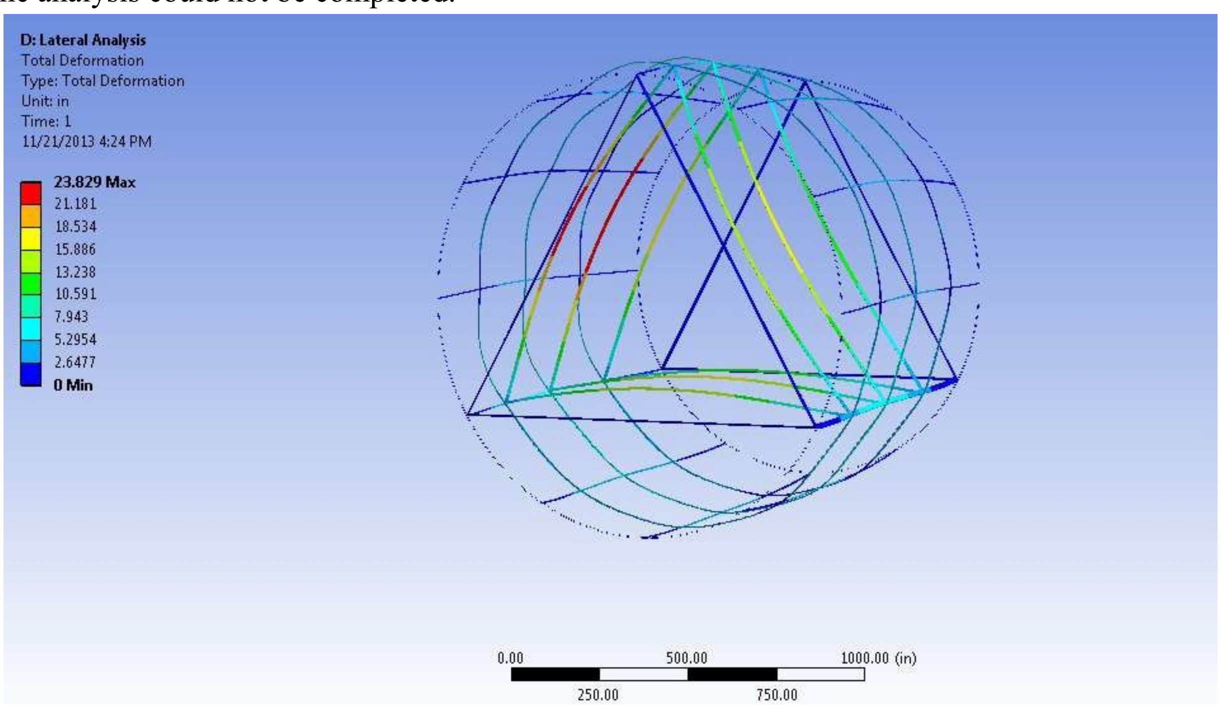


Figure 25 structural deformations due to lateral gusts

Seen in figure 25 is the total deformation on the vehicle. It is seen that the maximum deformation of 23.829 inches occurs on the primary structure. It is also noted that the secondary structure deforms as well. This should be minimized with the tensioning cables as well as the external material.

The material to be applied to the exterior of the structure that will shield the balloons from debris as well as make it more aerodynamic is a polyester material with different coatings in order for it to be water resistant as well as UV-resistant. These coatings include a PVF layer that has excellent weathering capabilities and is proven in the new Zeppelin NT semi-rigid airships. The calculated mass of the external material is 4383 lbm. This is calculated with respect to a weight of 0.0512 lbm/ft^2 and a surface area of 85609 ft^2.

6.3 Thermal Loads on an Airship

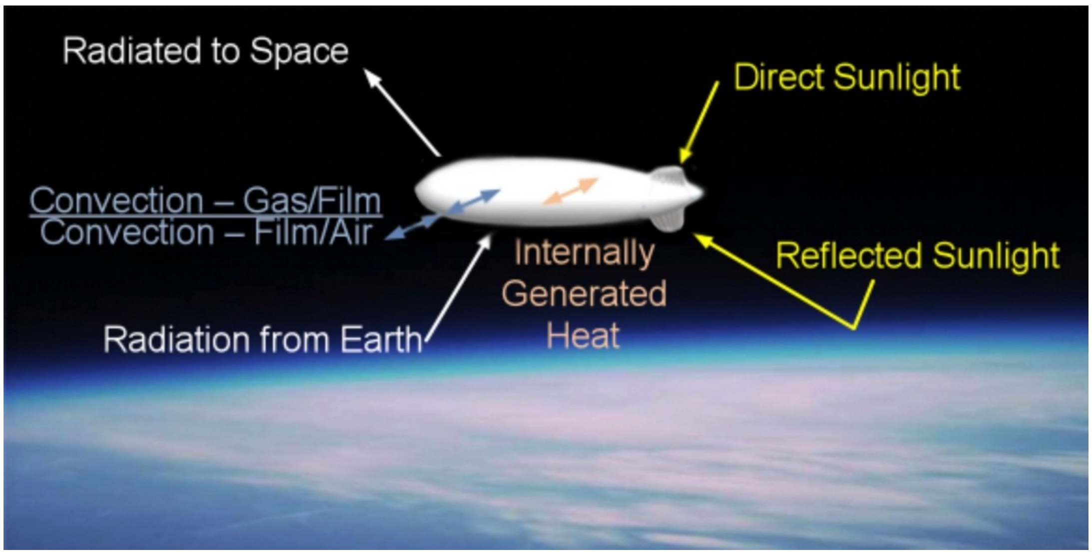


Figure 26 Heat loads on an airship. (Keck, 2014)

A brief investigation was also carried out into the thermal loads on the airship. From similar sources and research, it was found that the airship experiences significant thermal loads at higher altitudes. Especially, if it they designed for use as a stratospheric observation platform. The proposed airship as mentioned earlier has a service ceiling of 12,000ft. Therefore, most thermal loads can be neglected for this stage of the investigation to focus on the aerodynamics and control.

6

1 AERODYNAMICS

After obtaining a preliminary weight, size and structural design of the airship, the aerodynamics of this proposed airship could be investigated. The design of the airship is based on hybrid airship technology that means the total lift for flight will be a combination of both aerostatic and aerodynamic lift. The advantages of this 'hybrid' design include greater efficiency compared to conventional designs, and the ability to glide in case of a complete loss of aerostatic lift. A wider fuselage/gas envelope is desired to maximize the aerodynamic lift. For an optimum reduction in form drag, the airship should be long and slender. But a long slender body will not produce lift and it does not suit for a hybrid airship. This brings up design dilemma that is tackled in this section.

The classic airship design consists of an axisymmetric, teardrop-shaped hull with a hanging empennage (or gondola) and tail fins for stability. The axisymmetric configuration used in this analysis captures the essential aerodynamic characteristics of typical airships, while facilitating a mathematical development of the model. The buoyancy force provides an energy-free form of lift. The geometry of this configuration is then used to develop a general aerodynamic model for the airship. The equations of motion with added mass and inertia are developed. This is achieved through the aerodynamic study of conventional teardrop shaped airships from the past. It should be noted that since airships achieve lift through buoyancy, thus requiring very less power than traditional fixed wing aircraft.

7.1 Lift

The aerodynamics of airship hull can be divided into the inviscid and viscid part. The inviscid aerodynamics can be calculated by the slender body theory. While the viscid aerodynamics can be calculated by Allen's viscous cross flow theory. Airships produce high lift using gases, which are lighter than air. Hydrogen and Helium are the most common gases used to generate lift for the airships. Currently Helium is the material used to generate lift because the lifting capacity of Helium is 0.070 lb/ft^3. Though Hydrogen provides a higher a lifting capacity its volatile and flammable nature makes it unsuitable for this design. The volume of the hull defines the buoyant lift capability of the airship, and determines the maximum attainable altitude. It is first necessary, however, to develop some relationships between mass, volume, and gas densities, as governed by aerostatic principles.

The length of the airship designed is 300ft with a volume of 1.901 million ft^3. The lifting upward buoyancy force, which is equal to the weight of the displaced air, is given by

$L_G = V_N \rho_A g$

Where,

V_N □ net volume of displaced air

ρ_A the density of air
g acceleration due to gravity

Subtracting the weight of the lifting gas (Helium), the net lift L_N is given by:

$$L_N = V_N(\rho_A - \rho_H)g \quad = 111200 \text{ lbs}$$

As the airship rises, the density of Helium decreases along with the atmospheric density. This variation in internal lifting gas volume is achieved through ballonets – bags of air inside the hull, which expand, and contract to regulate the internal pressure (and thereby the volume). At the launching altitude (assume sea level), the density is at its highest value. The ballonets are expanded to their maximum volume, and V_N is at a minimum. As the airship begins to rise, the ambient density and pressure both fall, and air is automatically ejected from the ballonets to match the falling pressure. Clearly, at some point during the ascent, the ballonets will become completely empty. At this point, no further expansion of the lifting gas volume is possible because the net volume has reached a maximum value, Vmax. This point is termed the "pressure altitude". It can be shown that the net lift is constant over all altitudes, up to the pressure altitude. This is based upon the assumption that the density of the lifting gas changes at the same rate as the atmospheric density.

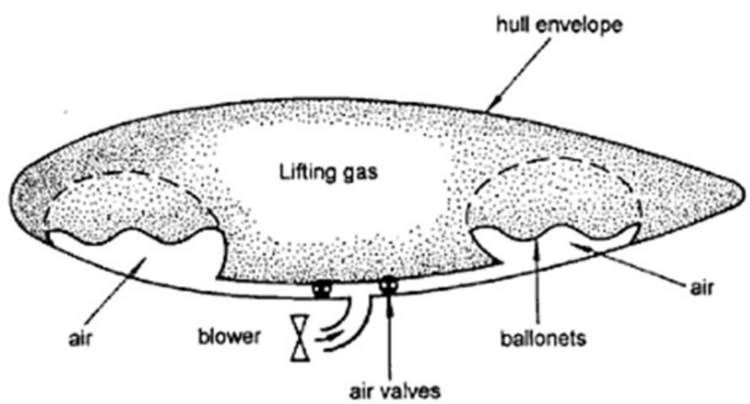


Figure 27 Classic Ballonet Systems in an Airship

To maintain vertical equilibrium through the buoyancy force alone, the net lift must equal the combined weight of the airship structure, systems and payload.

$$L_N = (M_{structure} + M_{payload})\, g$$

Where,
$M_{structure}$ → Mass of the structure and all systems
$M_{payload}$ → Represents the payload mass.

7.2 Drag

With the size and shape of the airship now defined, the expected drag can be calculated at the desired operating condition. The usual expression for the aerodynamic drag force on a body based on Hoerner's, the axial drag of the airship hull is 8184N.

Calculated through:

$$D = \frac{1}{2} \rho U^2 A C_D = 8\text{kN}$$

Where
ρ → The atmospheric density
U → The free-stream velocity
A → The reference area
C_D → The non-dimensional drag coefficient

The drag on a typical airship body has significant contributions from both skin friction and pressure. The aerodynamic model presented here was developed using the procedure outlined by Jones and DeLaurier. This model includes expressions for axial force, normal force, and pitching moment on an axisymmetric airship hull with 4 equally sized tail fins – 2 horizontal and 2 vertical. The equations are valid for un-separated flow only. The geometric configuration of the complete airship with fins and gondola is shown in the following figure. It is flying at an air speed velocity of V_o and at an angle of attack. The forces are labeled as X, Y, Z, and the moments as L, M, N. The forces and moments on the hull are evaluated from the nose to the start of the fins. Aft of this point, the hull and fins are evaluated together.

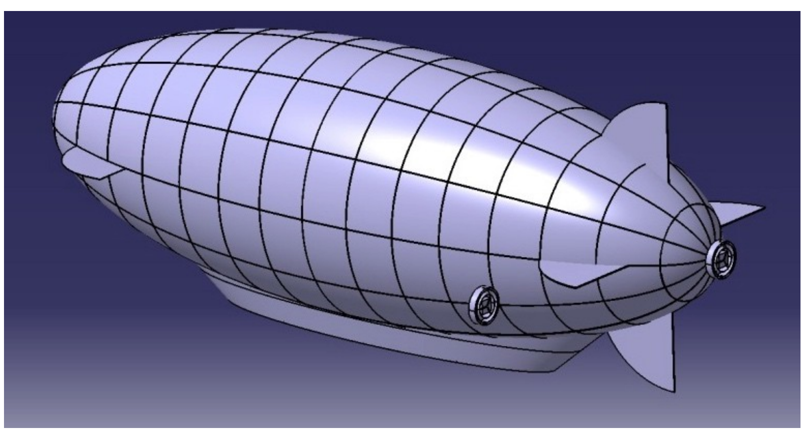


Figure 28 Axisymmetric airship hull with four equally sized tailfins

7.3 Fin Sizing

The aerodynamics of airship fins can also be divided into the linear and the nonlinear parts. The linear aerodynamics of fins is calculated by the approach of panel method [24]. The nonlinear aerodynamics of fins is calculated by the Polhamus-Lamar suction analogy method. The interference of body and fins are included in this model by considering the vortexes of airship hull. The detail calculation formulas of airship fins can be found in reference [23]. The fin area was calculated based on the references mentioned above and resulted in area of 500 square feet.

7.4 Airfoils

The selection of the airfoil for the horizontal and vertical fins is chosen to be S1223 based on high lift, low Reynolds number, and minimum drag. The horizontal fins generate lift that is accompanied by residual aerodynamic pitching moment, which has to be eliminated. The required lift to eliminate the lift in opposite direction with minimum drag could be accomplished with a cambered airfoil. The following figures give the lift, drag, and pitching moment characteristics for the airfoil at various angles of attack. Airfoil selection criteria:

- **High lift, low Reynolds number**
- **To eliminate the residual pitching moment**
- **Low drag**
- **Cambered Airfoil was chosen to meet the above requirements**

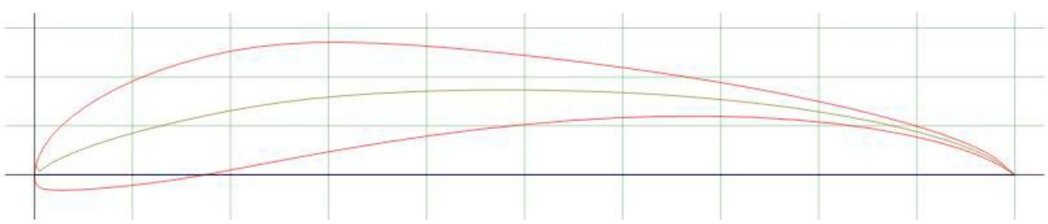


Figure 29 S1223 Airfoil profile (Avl, 2014)

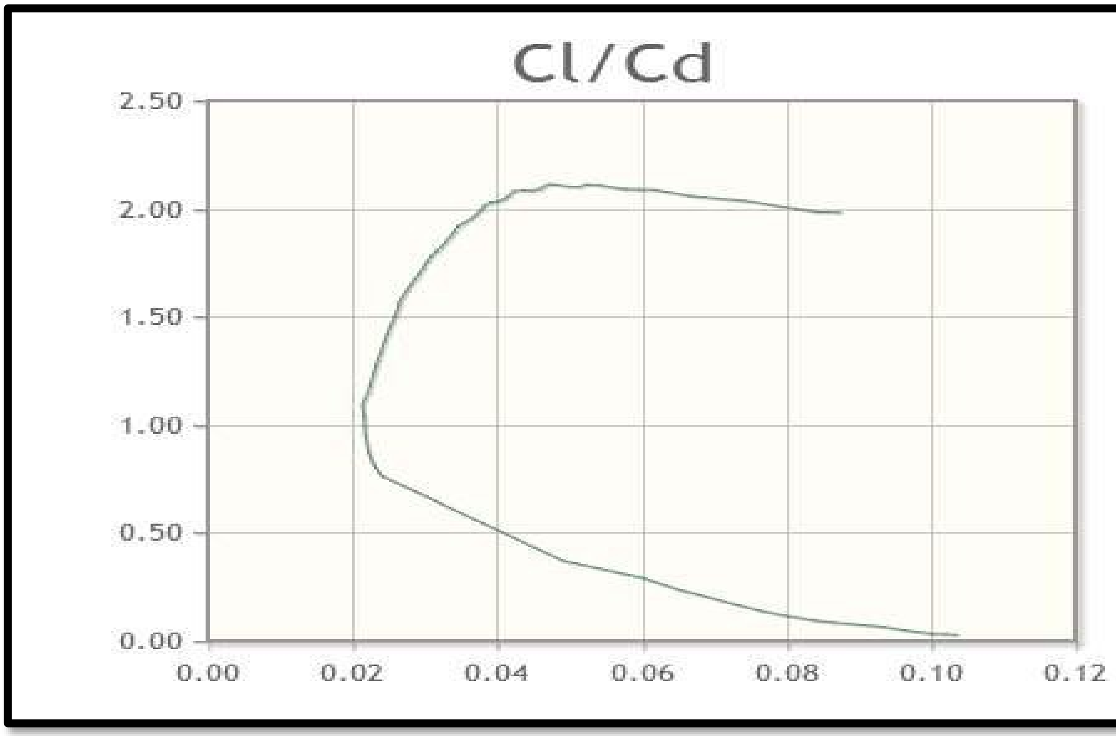


Figure 30 Airfoil drag profile

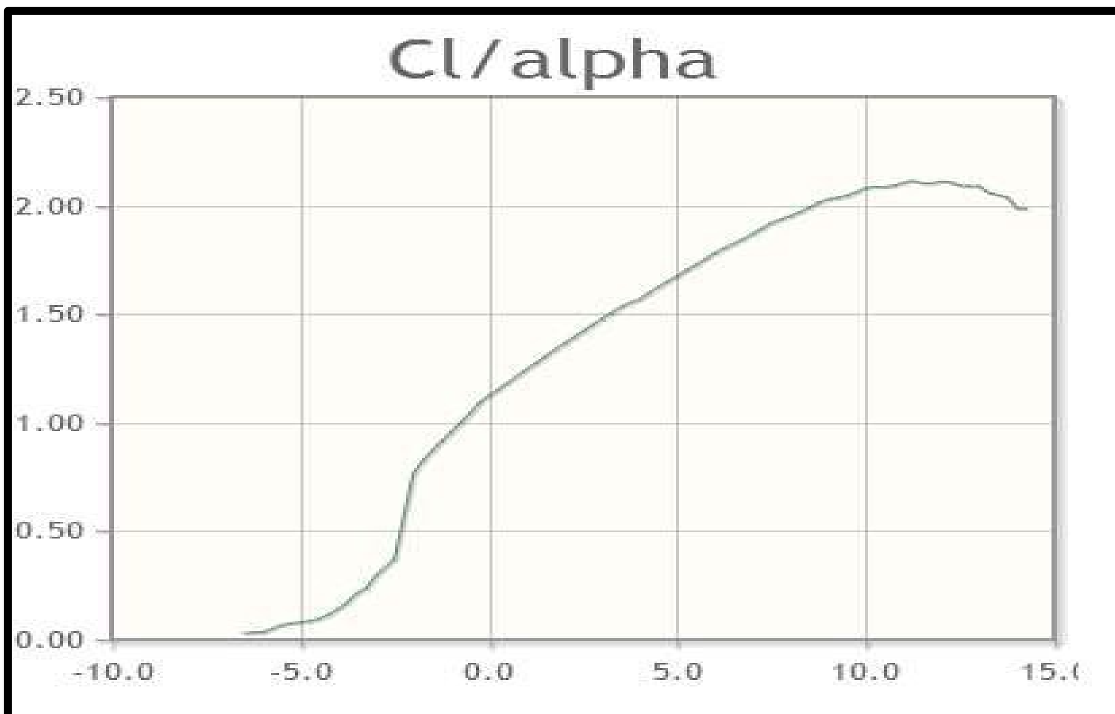


Figure 31 Coefficient of Lift vs. Alpha

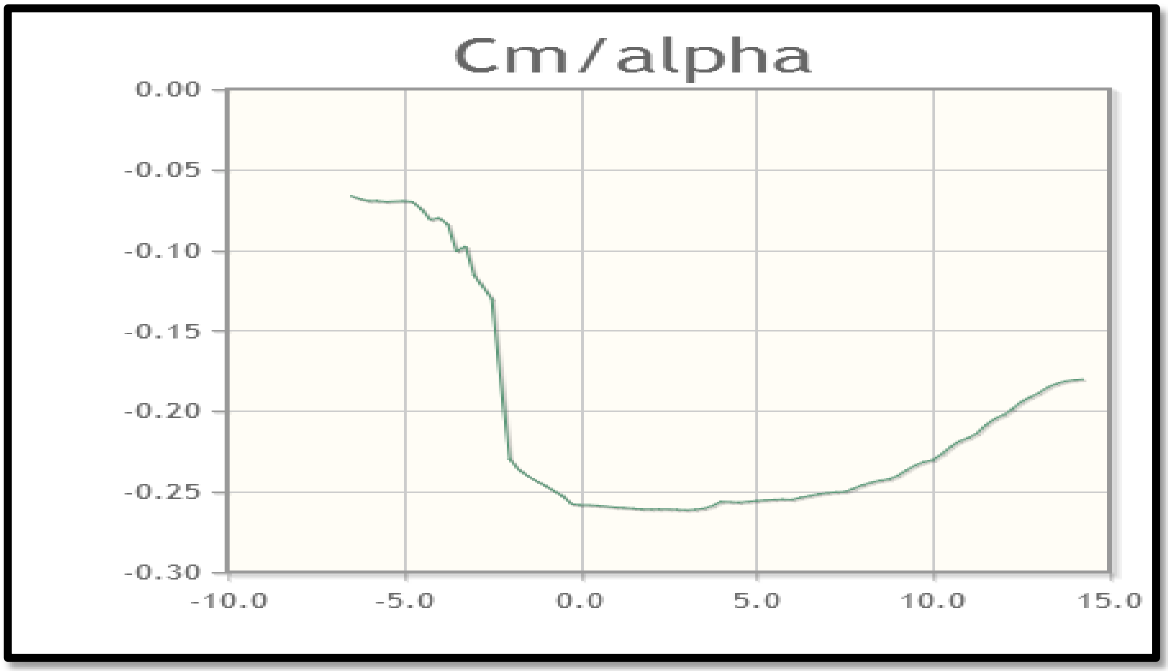


Figure 32 Moment Coefficient of the airfoil

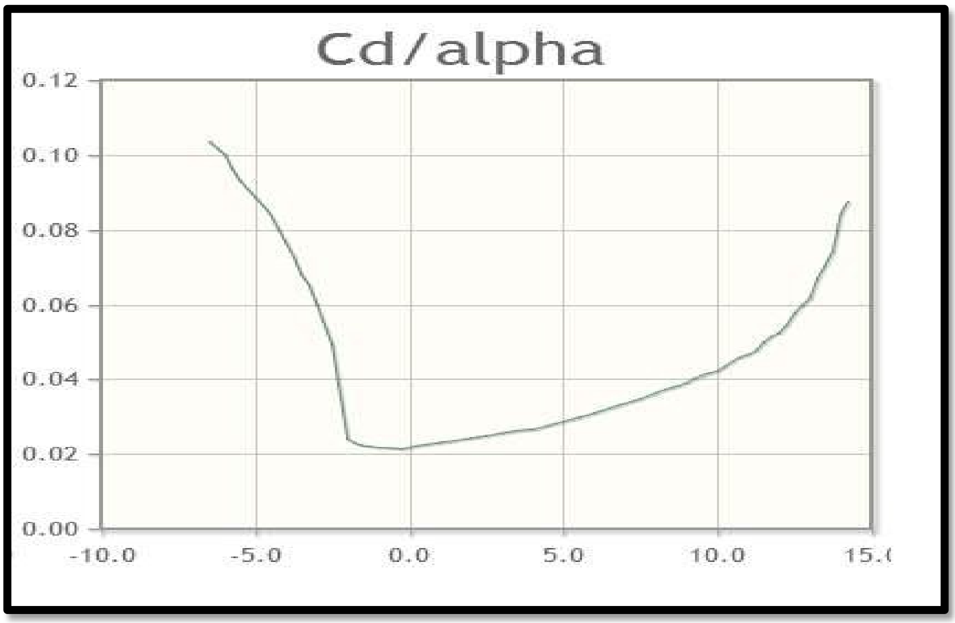


Figure 33 Coefficient of Drag

7

1 STABILITY AND CONTROL

8.1 Approximate models of Longitudinal and Lateral modes

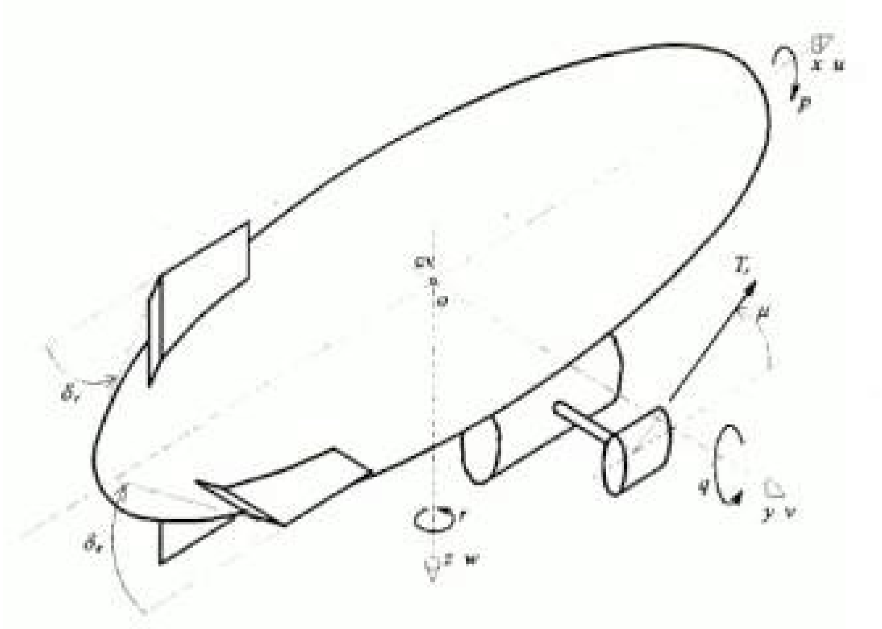


Figure 34 Axis System for derivation of stability of an Airship. (Cook, 2004)

Using the axis system indicated above, the longitudinal state equation can be written as assuming fixed controls:

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \mathbf{A} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix}$$

The stability modes are characterized by the zeros of the characteristic polynomial.

$$\Delta(s) = \det[s\mathbf{I} - \mathbf{A}]$$

The state matrix may be simplified and approximated by the polynomial:

$$\Delta(s) \cong (s - x_u)(s - z_w)\left(s^2 - m_q s + \left(\frac{m_w z_\theta}{z_w} - m_\theta\right)\right)$$

$$\cong (s - x_u)(s - z_w)(s^2 - m_q s - m_\theta)$$

Since, at low speed $m_\theta >> \frac{m_w z_\theta}{z_w}$.

Thus to a good approximation the low speed longitudinal stability modes can be characterized as follows:

- **Surge Mode (s-xu)**
- **Heave subsidence mode (s-zu)**
- **Pendulum Mode (s^2-m_qs-m_Θ)**

At moderate to higher speeds the complete solution becomes:

$$a = -m_q \quad b = -z_w \quad c = \frac{m_w z_\theta - m_\theta z_w}{m_q}$$

Therefore the polynomial is:

$$\Delta(s) \cong (s - x_u)(s - m_q)\left(s^2 - z_w s + \left(\frac{m_w z_\theta - m_\theta z_w}{m_q}\right)\right)$$

$$\cong (s - x_u)(s - m_q)\left(s^2 - z_w s - \frac{m_\theta z_w}{m_q}\right)$$

And Since at high speed

$m_\theta z_w >> m_w z_\theta$.

Thus good approximations of the modes at higher speeds are characterized as:

Speed subsidence, or surge mode	$(s - x_u)$
Pitch subsidence mode	$(s - m_q)$
Longitudinal pendulum mode	$\left(s^2 - z_w s - \frac{m_\theta z_w}{m_q}\right)$

$$\begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \end{bmatrix} = \mathbf{A} \begin{bmatrix} v \\ p \\ r \\ \phi \end{bmatrix}$$

8.2 Lateral Directional Stability Modes

The stability modes are characterized by the zeros of the characteristic polynomial,

$$\Delta(s) = \det[s\mathbf{I} - \mathbf{A}]$$

$$\mathbf{A} = \begin{bmatrix} y_v & y_p & y_r & y_\phi \\ l_v & l_p & l_r & l_\phi \\ 0 & 0 & n_r & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

By omitting significant elements and simplifying;

$$\Delta(s) \cong (s-n_r)\left(s^3 - (l_p + y_v)s^2 - (l_\phi + l_v y_p - l_p y_v)s + (l_\phi y_v - l_v y_\phi)\right)$$

This can be simplified to:

$$\Delta(s) \cong (s-n_r)\left(s + y_v - \frac{l_v y_\phi}{l_\phi}\right)\left(s^2 - \left(l_p + y_v - \frac{l_v y_\phi}{l_\phi}\right)s - l_\phi\right)$$

Thus, a good approximation to lateral-directional stability modes can be characterized as follows:

Yaw subsidence mode	$(s-n_r)$
Sideslip subsidence mode	$\left(s + y_v - \frac{l_v y_\phi}{l_\phi}\right)$
Oscillatory roll mode	$\left(s^2 - \left(l_p + y_v - \frac{l_v y_\phi}{l_\phi}\right)s - l_\phi\right)$

8.3 Longitudinal Stability Modes:

Surge Mode:

Speed subsidence or surge mode is triggered by an axial aerodynamic drag and this can be characterized as lag response time for the axial speed. This mode is neutrally stable at zero velocity and becomes more stable as the airship's speed increases. For both high speed and low speeds, a force in 'u' direction can approximate the stability mode and the approximate transfer function is ($s-x_u$). Since the cruise speed of the Proposed airship is relatively fast compared to conventional Airships such as the Hindenburg and Zeppelin NTs the compared stability of this mode will be high.

Heave Pitch Subsidence Mode

Heave Pitch subsidence mode is caused by transverse aerodynamic drag. This mode can be characterized as a lag in response time of elevator step at different speeds. The response changes depending on speed with poor response at slow speeds and better response at higher speeds. At low speeds, vector thrust is necessary and therefore, the heave mode is approximated by force in w direction (z_w). During high speeds, the pitch mode is approximated by pitching moment due to pitch rate (m_q). The transfer function that represents these modes are ($s-z_w$) and ($s-m_q$). This means that at lower speeds thrust vectoring is more effective than aerodynamic directional control.

Pendulum Mode

Pendulum Mode or Pitch incidence oscillation mode is caused by coupling of moment due to pitch rate, moment due to pitch angle, force in 'u' direction and force in 'w' direction. During low speeds, the pitch rate is combined with 'u' and as the airship increases in speed, it causes coupled moments known as 'Munk' moment. Munk moment is defined as moment on a body due to steady translation, which causes the system to destabilize. Therefore decreases the damping ratio at a range of speeds. At low speeds, the pendulum mode is approximated by ($S^2-m_qS-m_\theta$). During high speed, the pendulum mode is approximated by the transfer function ($S^2-z_wS-m_\theta z_w/m_q$).

Lateral Stability Modes: Yaw Subsidence Mode

Yaw subsidence mode is caused by the yaw rate and velocity in the 'v' direction. It can be approximated by moment due to roll rate 'n_r'. At low speeds the mode is very stable and therefore the pilot usually has hard time changing the yaw-direction of the airship. This mode is approximated by the transfer function ($s-n_r$). The difficulty in controlling the yaw-direction of an airship can be expected due its long body structure leading long moment arms.

Sideslip Subsidence mode

Sideslip subsidence mode is caused when the motion in the 'v' direction and yaw rate are coupled with roll angle and roll rate. The forces in the 'v' direction and moment due to roll rate can approximate sideslip subsidence mode. The characteristic transfer function is ($S+y_v-l_vy_\varphi/l_\varphi$).

Oscillatory roll mode

Oscillatory roll mode is similar to pendulum mode in the cases that both are caused the munk moment, which is moment due to roll rate and forces in 'v' direction and roll angle. The aerodynamic forces increase at high speeds and damping ratio decreases. The transfer function that approximates this mode is [S2-(lp+yv-lvyφ/lφ)S-lφ].

The discussion of these stability modes together with the step input plots at cruise shows Proposed airship's stability as an airship especially in cruise mode.

8.4 Stability analysis using MATLAB based on the proposed

models and modes

In the case of stability analysis the cruise mode was selected as the focus of this analysis. This was mainly because the proposed airship will be spending most of its flight time cruising. The following analysis is carried out in various cruise conditions and then a brief discussion is provided on various longitudinal and lateral modes. MATLAB was used for this preliminary stability analysis. The code for the analysis is attached in the appendix. The three following plots show the step input response of the airship travelling at cruise speed of 50 knots and three elevator configurations. The three configurations are 1^o, 5^o and 10^o. These configurations do not include any thrust vectoring only aerodynamic control is considered. All response plots can be observed to be stable due to the response settling over a specific time on a specific value after an initial perturbation.

8.4.1 Longitudinal responses

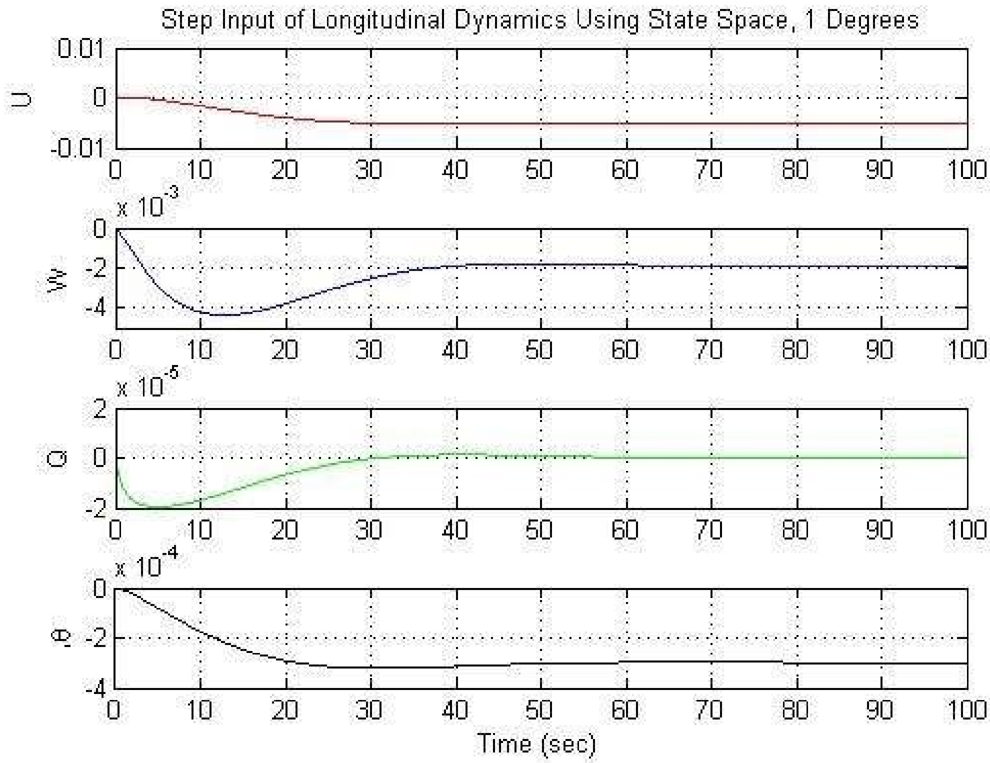


Figure 35 Step input of Longitudinal Dynamics using state space for 1-degree elevator input

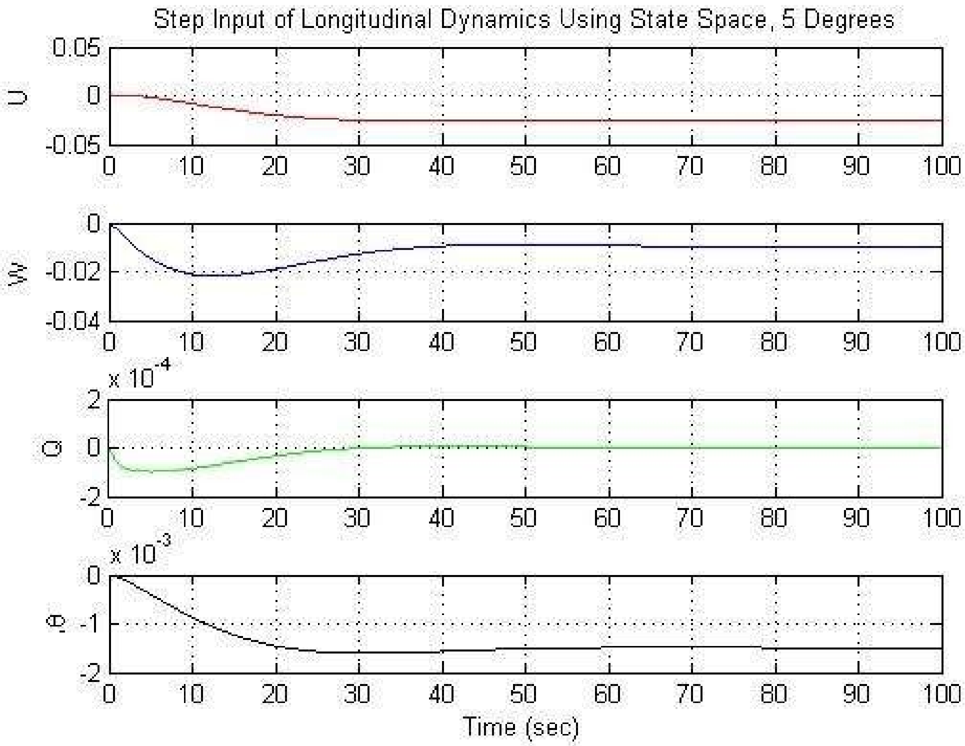


Figure 36 Step input of Longitudinal Dynamics using state space for 5-degree elevator input

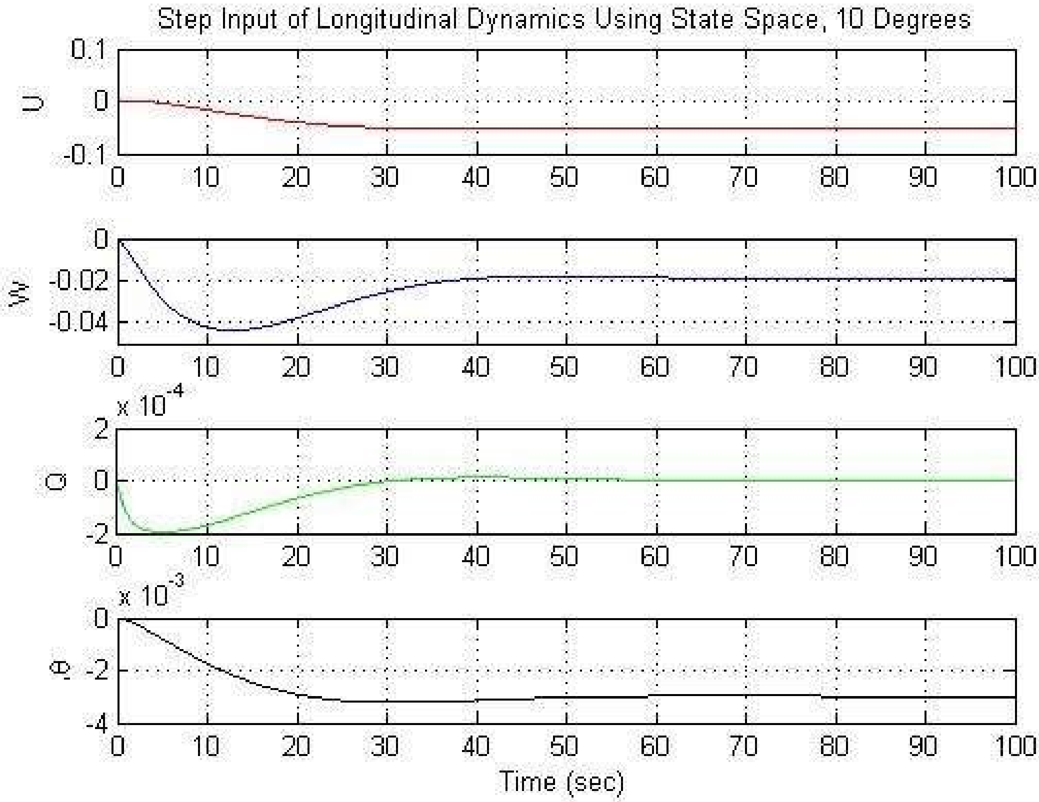


Figure 37 Step input of longitudinal Dynamics using state space for 10-degree elevator input

From the first plot it can be seen that the axial velocity U decreases slightly from 0 to nearly -0.01 to the positive elevator input leading to greater drag due to the pitching up of the airship. This settles to the lower value due to the induced drag mentioned earlier. This drop in velocity is more significant as the step input increases in value. For the 5 and 10-degree plot this becomes more apparent where the drop in U is closer to -0.05 and -0.1 respectively. The pitch rate ‘Q’ can be seen to perturb initially to a negative value but settling in 40~50 seconds in all three degree configurations. The Normal velocity ‘W’ decreases after the initial step input but also settles to a new non-zero value around 60.

8.4.2 Lateral Responses

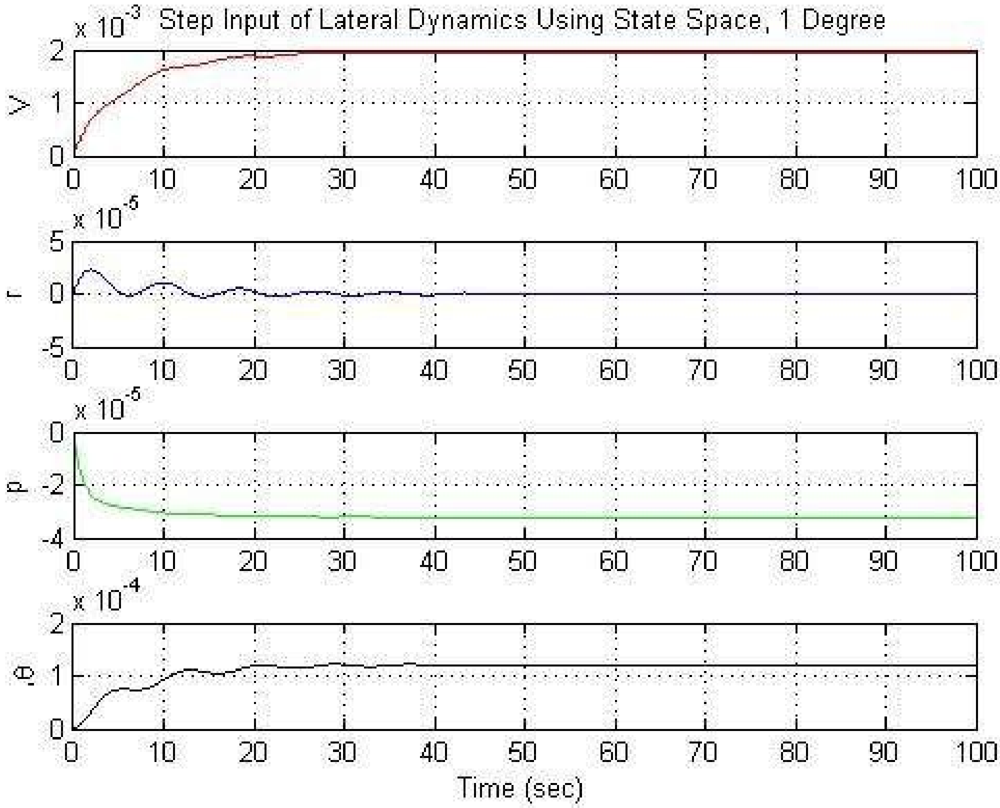


Figure 38 Step input of Lateral Dynamics using state space representation for 1-degree input

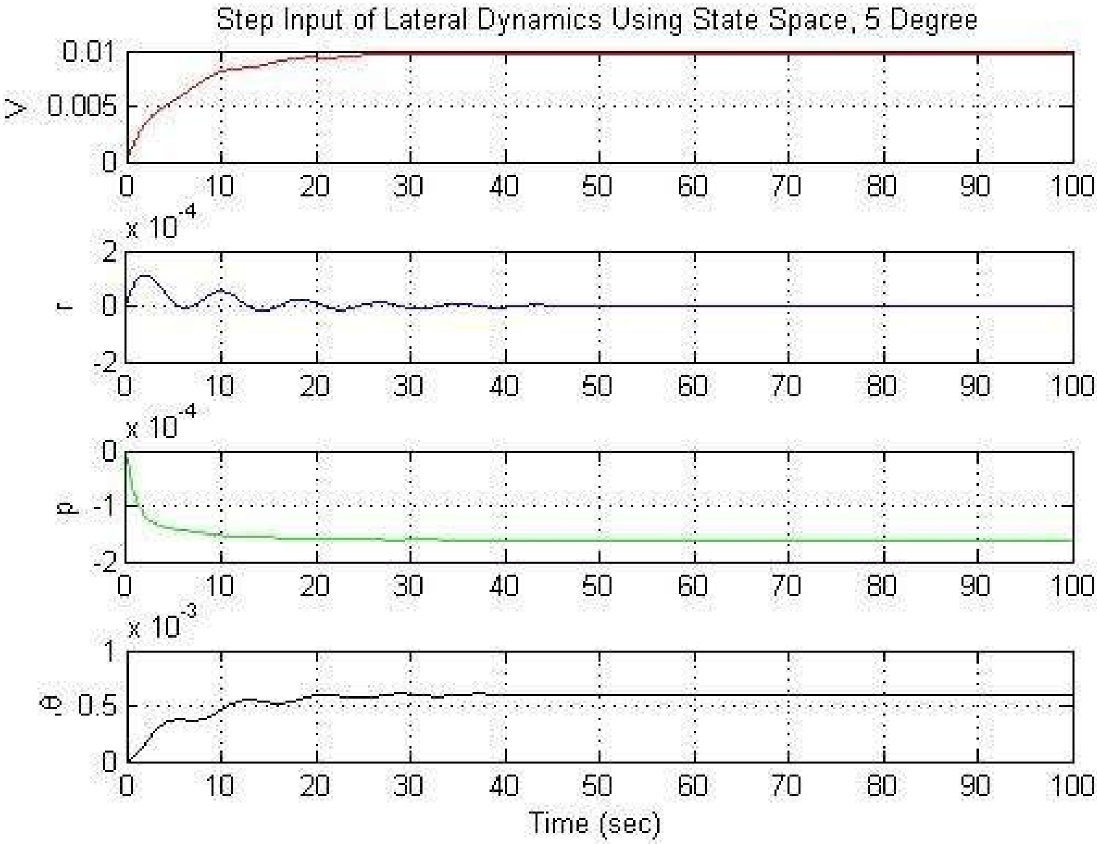


Figure 39 Step input of Lateral Dynamics using state space for 5-degree input

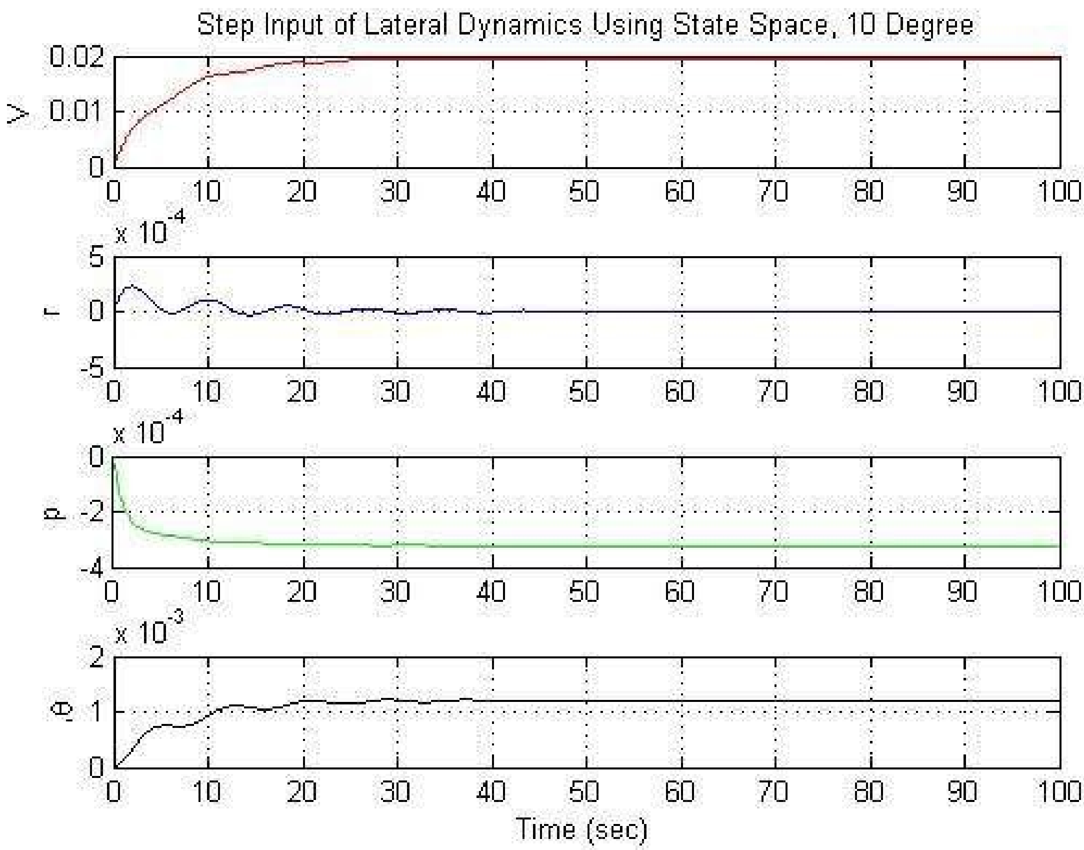


Figure 40 Step input of Lateral Dynamics using state space for 10-degree input

The Lateral dynamics of the airship consist of the lateral velocity, roll rate, yaw rate, and pitch rate. In the above graphs, these rates were calculated for different degree angles for the dynamics of the airship. As can be seen, when the system is given a small perturbation of the lateral dynamics, the system tends to oscillate for a while, but then stabilizes. This is due to the size of the airship. The key to note here is that the system is in fact stabilizing into a turn. Once the step input was given, the ship started its turn immediately, as can be seen in the yaw rate plot. It is stable because it levels off in its turn instead of returning or continuing. As seen below, the pitch rate tends to oscillate before it stabilizes. This is most likely due to the roll control surfaces counteracting the yaw control surfaces. The full state space equations and transfer functions is included in the appendix.

These results indicate that the control surfaces such as the elevator have very little effect on the control of the airship. Not only are the magnitudes of the response very small, additionally the time to reach the desired state is also very slow. Thus it becomes very clear that thrust vectoring must be implemented to augment the stability of this airship and improve its flight characteristics. The lateral mode analysis is forgone to address this control issue and possible redundancy systems.

8 POWER AND SIZING

9.1 Power plant Selection

After several recalculations and refinements to obtain the total drag of Proposed airship, (8284 lbF), it was found that the propulsion system would change from the three IO-720's to three PT6A-60AG engines. This will affect the entire system, but the changes where done to assure mission requirements and will optimize the current design.

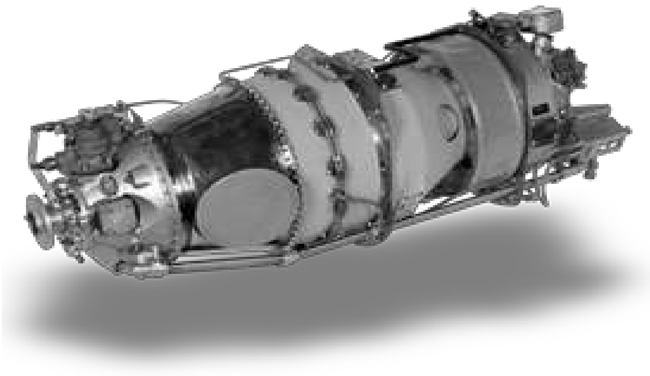


Figure 41 Power-plant selection: PT6A-60AG

Two of the engines will be located laterally, to assist with accent and descent, and one will be at the rear, for pure thrust generation, as can be seen in Power Plant 2.

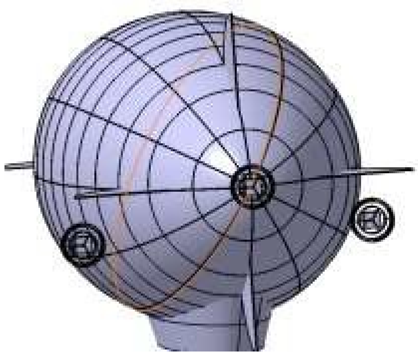


Figure 42 Triple Engine configuration

Each engine delivers 1050 SHP, and will be mated to a 9' MT-Propeller designed to the specs in Power plants 3 and 4.

Initial Conditions:
Drag Force =T = 554.67 lbF/engine

$\rho = 0.001512\ slug/ft^3$

Dprop= 9'

V = 50 KTS = 84.4 ft/s η = 60%

n=33.125 rev/s

9.2 Thrust Calculations

Using these conditions, the Coefficient of thrust C_T can be calculated:

$$C_T = \frac{T}{\rho n^2 D_{prop}{}^4} = \frac{554.67}{(0.001512)(33.125)^2(9)^4} = 0.0509$$

With the previous calculation and with the help of propeller static thrust charts; the selection was done so CT/Cp would be 2.4 finding that the best possible CL would be 0.300.

$$C_P = \frac{C_T}{2.4} = \frac{0.0509}{2.4} = 0.0212$$

$$J = \frac{V}{nD} = \frac{84.4}{(33.125)(9)} = 0.2831$$

After more calculations it was found that the Coefficient of Power (Cp) was 0.0212 and an Advance Ratio (J) of 0.283, with the help of Power plant 4, the efficiency of the propeller is 60%.

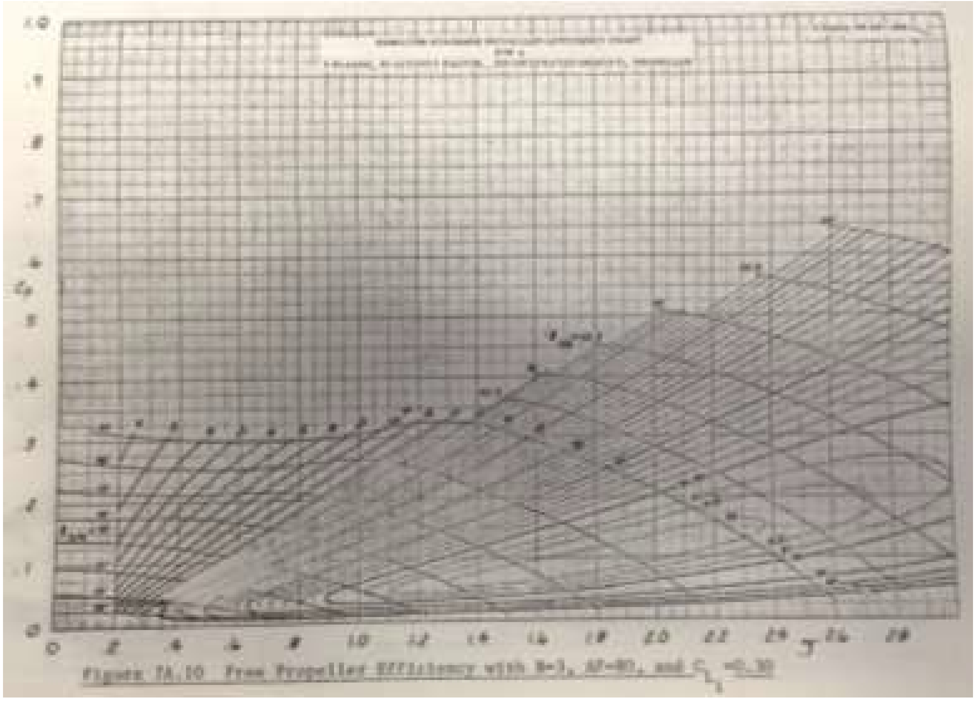


Figure 43 Hamilton propeller efficiency chart for thee-blade arrangement. (Cook, 2004)

Activity Factor of 80 and a Lift Coefficient of 0.30

With these finding, it can be commented that these engines will easily propel Proposed airship over 50 KTS, running at less than 60% of throttle while still delivering a fuel rate of about 26 gal/hr.

$$\eta = \frac{P_a}{P_{Engine}} = \frac{T * V}{P_{Engine}}$$

$$P_{Engine} = \frac{T * V}{\eta} = \frac{4110 * 84.4}{.6} = 578{,}140\ \frac{ft - lbF}{s} = 1051.16\ bhp$$

Engine @ 55% 1146.7 bhp = 630696 $\frac{ft\text{–}lbF}{s}$

$$T = \frac{P_{Engine} * \eta}{V} = \frac{630696 * .6}{84.4} = \mathbf{4483.6\ lbF}$$

Even though a reciprocating engine might be best for the other applications at this altitude (12,000 ft). Due to the dimensions of Proposed airship, a turboprop will still somewhat maintain fuel efficiency when cruising and will have the necessary power to speed up and will be able to fight any cross winds if necessary.

9.3 Fuel Estimation

Averaging the fuel flows at different throttle percentages, an approximate can be determined for the amount of fuel needed for the 30 hour flight, which will decrease from the previous estimate of around 27,000 lb of fuel for 60 hours to about 13,020 lb or about 2350 gallons. On a more realistic level, the fuel that travels to the engines is considered to be unusable fuel. The approximate distance from the main fuel tank to the engines is about 80 feet. Assuming that the diameter of the fuel line is about 1 inch; the airship will have about 10 gallons of unusable fuel onboard.

9.4 Thrust Vectoring

To reach the desired cruise altitude of 12,000 ft faster by assisting the initial lift, the two laterals PT6A-60AG's will utilize the COTS Woodward Tilt Rotor actuator system, utilized in the V-22 Osprey and in the BA-609. This system is a fully functioning thrust vectoring system. It will assure full synchronization between the two engines while performing the maneuver. As can be seen below, the engine will sit inside of the system and have the capability of being turned 90 degrees in most directions. The engines will also be able to be turned slightly upwards and downwards in order to allow the ship to ascend or descend.

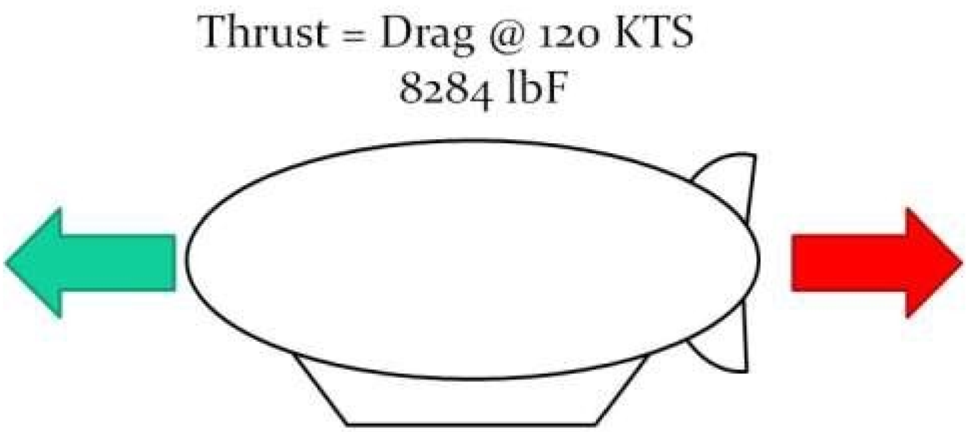


Figure 44 Thrust equals drag analysis

9.5 Sprint & Drift methodology

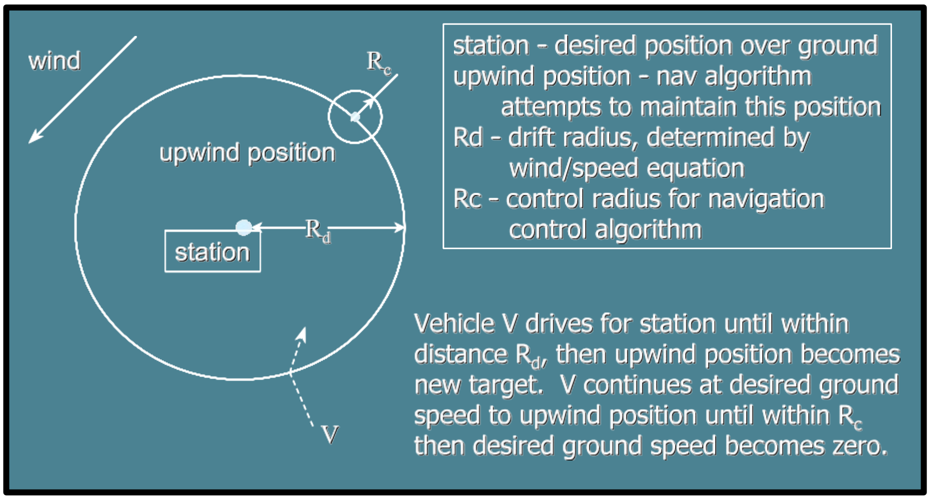


Figure 45 "Sprint and Drift" method of navigation

Sprint and drift: A major factor affecting airship size is the mass associated with the power generation and energy storage systems required for airship propulsion. The efficiencies of the solar cells and the energy storage system are very important. Propulsive energy mass minimization is one consideration when selecting the operational navigation modes of "station-keeping" or the "Sprint and Drift" approach. Figure 45 shows how the stratospheric airship flight controller may implement the "Sprint and Drift" approach for station keeping.

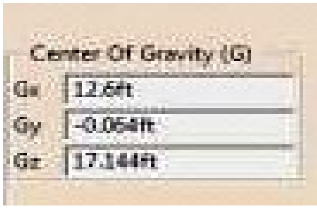
What does "Sprint and Drift" mean? Assuming that the average wind and average airship speeds are equal, the airship sprints upwind of the station keeping point during the day at high speed, and during the night, drifts back over and then downwind of the station keeping point at a slower nighttime speed. This technique can significantly reduce the total mass for the propulsion power system. For some airship designs, the "Sprint then Drift" technique reduced the propulsion power mass by 33% below an airship of equivalent volume that could achieve the same speed at night as during the day.

How does the "Sprint and Drift" approach save weight? For an example airship design, it takes 9.1 grams of equipment to produce 1 watt of power during the day. It takes 48.2 grams to produce 1 watt of power from the fuel cell system for a 14- hour night. It is advantageous from a mass minimization standpoint to spend a little more energy during the day in order to conserve power during the night. The calculation is not simple, but for these airship designs, the minimum mass is achieved with a night-to-day speed ratio of 0.46, thus to achieve an average air speed of 15 m/s for a 10 hour day and a 14 hour night, the day speed is 21.9 m/s and the night speed is 10.1 m/s.

9 SYSTEMS ARCHITECTURE & CONTROL ACTUATION MECHANISMS

10.1 Flap System

The airship will have 6 pitch control systems within the upper area of the airship. The positioning of them will be based on the total load of the ship. As shown in the inertial properties of the airship, it is basically centered, so the elevators will be positioned in the front and back of the ship on both sides. The reasoning for the excess amount of the elevators is because they will all run through a controller that will also keep the ship from rolling. This system will also allow the ship to have stronger control of its pitch attitude due to the fact that the ship should not change pitch too much. The system will be updated in real time with a gyro that will be programmed to resist this pitching motion. Given the size of the airship, they will be steady smooth transitions and not quick adjustments as seen in a fixed-wing aircraft.



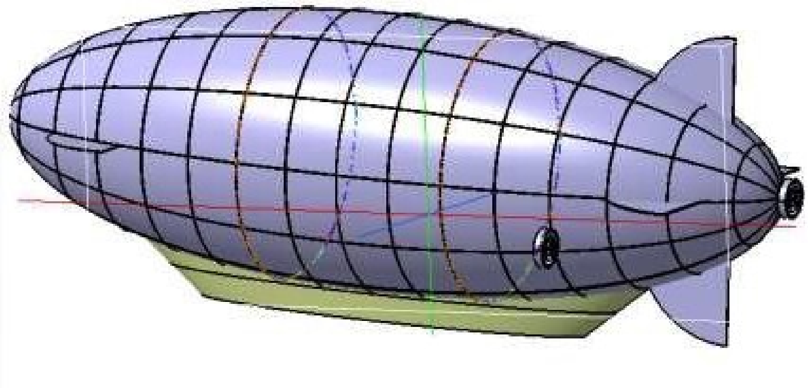


Figure 46 CG of the proposed airship

Within the tail design of the airship, there will be two main rudders on the back. They will be positioned within the upper lighter-than-air section of the airship. The mechanism that will power these rudders will consist of pneumatic actuators that are controlled through a controller by the pilot. In other words, they will be fly-by-wire.

10.2 Ballonet System

The airship will also have a ballonet system that will assist in pitch control while ascending and descending to and from cruise altitude. The system will consist of motors that that will compress the gas that are either in the front of the ship or the back, depending on whether it is ascending or descending. The compressed gas will be stored in on-board tanks that will be in both the front and rear of the ship. This will help keep the ship balanced and allow for steady changed in altitude for the passengers.

10.3 Fuel Tank Placement and Management

The style of tank that will be used for this ship will be made in such a way as to not cause extreme shifting during up or down lift. To achieve this, the tank will need to be made so that there are multiple tanks within. There will be a master pump that will extract fuel from the tanks simultaneously. The placement of the tanks will also assist in its non-ability to shift the airship. The tanks will be placed in the center of the ship above the storage area on the second floor of the main structure of the ship. A diagram of its placement can be seen in the Figure 14 below.

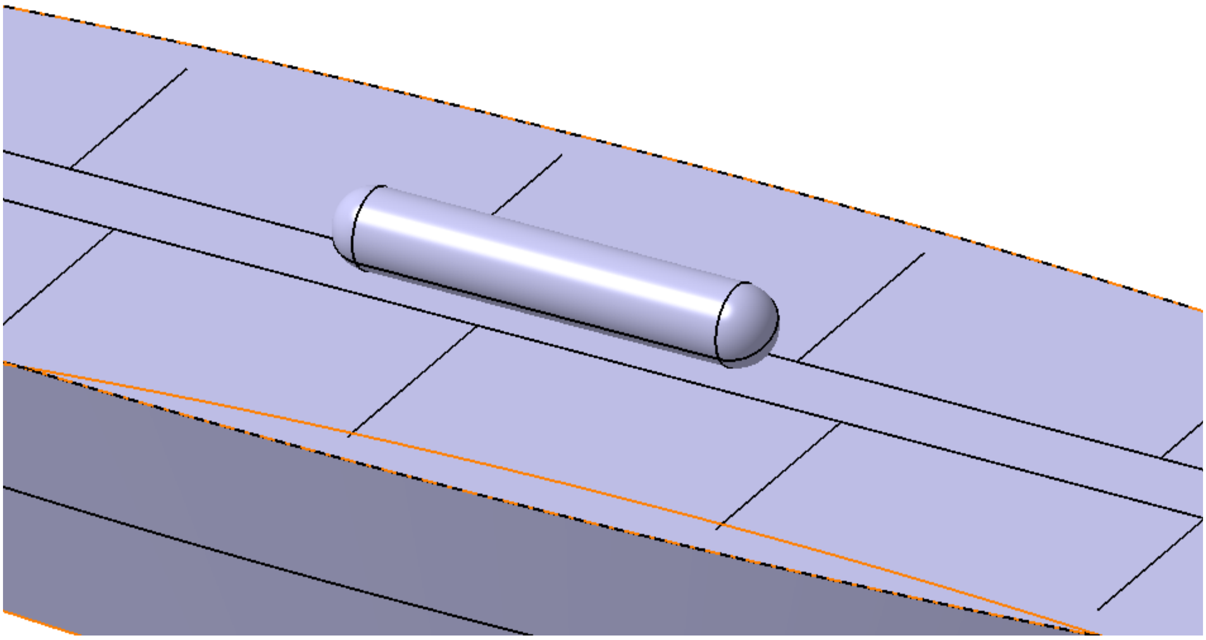


Figure 47 Fuel-tank placement

The amount of fuel that the ship will carry is also very important. To calculate this, the weight of the ship and its crew is calculated and referenced with the flow rate of fuel to all the engines for the estimated time of travel in order to obtain an approximate amount of fuel to carry onboard.

Of course, an allotted amount of extra fuel will be added to the total to account for emergency maneuvers, harsh weather, and heavier loads.

10.4 Buoyancy Control

The system that controls the buoyancy of the airship is the COSH system, which is the lift management system. It stands for the 'Control of Static Heaviness'. It is designed to compress approximately 10 percent of the total weight of the lifting gas therefore the airship will have approximately 7,450 lbs on the ground providing mooring without the need for cables (FAA requirement). When the system is activated, it fills the helium ballasts allowing the ship to attain neutral buoyancy. The COSH system will have pressure sensors in case the pressure inside a ballonet reaches critical it will remove helium until a safe pressure is attained. When descending, the COSH system will then compress the air in the ballasts. This is secondary to using the trim and tilt rotors for main controlled descent. This may be time consuming, but will not matter in normal conditions. In the case of an emergency, the system can simply exhaust the helium. This is provided in more detail in the Redundancy section of this report.

10.5 Landing gear arrangements:

Figure 48 Lockheed Martin's HALE-D airship, assisted taxying. (Keck, 2014)

Figure 49 Classical Tri-wheel landing gear arrangement. (Dietl, 2010)

Figure 50 Airship mooring tower for anchoring and passenger boarding. (Dietl, 2010)

Figure 51 Lockheed Martin's P-791 with ACLS arrangement (Dietl, 2010)

"Air-Cushion-Landing-System" or ACLS for all terrain landing and suction for anchoring

10 RISK ANALYSIS

For the proposed airship, it is essential to have systems that will prevent the aircraft from failing. Given its troubled past and departure from aviation this section on airship safety will focuses on various modes failure. The modes of failure can consist of helium deficiency, flap control loss, structural damage due to external properties, engine breakdown, and of course fire. For the safety of the passengers and the crew, this design will have a triple redundant system for each of the indicated failure criteria. Details of these safety systems are shown on the table below.

Table 3 Redundancy table for the proposed airship design

Helium Deficiency	Engine breakdown	COSH system loss	Flap Control
Spare tanks/ballonet system	COSH system stabilizer	Engine thrust vectoring	COSH system stabilizer
Activate COSH system	Power Shift to remaining engines	Manual COSH system activation	Electronic cable system
Ballast Dump	Flap system set for pitch control	Manual pump descent	Engine vector thrusting

If there were a helium deficiency in the system whereas the airship cannot maintain altitude, there will be a set of spare tanks that will automatically pump into a spare ballonet system inside the main system to obtain appropriate altitude. The COSH system will also activate to maintain the correct pitch level for the airship. In an attempt to maintain altitude, the final redundancy system for the ship is to dump the remaining excess weight such as water off the airship; approximately 9,000 lbs at most can be shed if needed. The airship could also be able to dump the fuel tanks as well in order to keep the system stable.

In the case of an engine break down, the airship will lose speed, but not necessarily altitude, unlike fixed wing aircraft. The COSH system will be activated to maintain pitch stability as the airship slows down. Another recovery system for the airship will be a power shift from the remaining engines. Instead of all three engines using 55% power, perhaps 2 of the remaining engines will use 70% power to keep the airship moving the same speed. Of course, in order to keep the same heading, the flap system will then change to account for the power shift. At the same time, the third redundancy will also kick in, which will adjust the pitch to maintain level flight conditions.

If there were a loss of the COSH system, the ship would automatically switch to thrust vectoring and flap systems in order to maintain proper altitude and pitch control. The second system will result to switching to a manual version of the COSH system, where the pilot will activate pumps that are directly run to each of the ballonets to control the pitch levels of the airship. If all fails with maintaining the proper attitude of the airship, a pump will then put the helium back into the tanks to generate a steady descent while maintaining proper pitch in order to make a safe emergency landing.

If the flap control system fails, thrust vectoring will be the main means of control for the airship. The COSH system will then keep the airship stable as it maneuvers. If there is an electrical problem that causes the flaps to fail, then it will automatically fall to the electronic cable system.

With these redundancy systems in place, the ship should be allowed to travel safely to its destination without major problems that would put people in harm's way.

11 CONCLUSION

This report touched briefly on many aspects of a modern passenger airship design. The key findings indicate that the classical teardrop shape has major complications in terms of effective stability control. Furthermore, structurally the balloon and hanging gondola design based of classical airships are not the most aerodynamic either. Thus requiring artificial assistance through thrust vectoring. This brings the focus to the safety analysis; it is observed that with multiple redundancy systems the safety cannot be guaranteed since the pilot has so little control over the massive structure.

The key understanding here was that none of the prototypes found through the literature review used the classical teardrop shape for the airship. This indicates that a more aerodynamic structure similar to blended wing body aircraft may have more desirable results. The limitations of this analysis were bound to classical designs for the abundance of data for verification of obtained results.

In conclusion, there are significant financial and technological barriers to the development of a lighter-than-air aircraft. Some of these challenges may take years to overcome. However, the challenges and consequent solutions presented in this paper provide a glimpse into how the airship can be a reality. Furthermore, the diverse applications discussed exemplify how industry changing the concept of lighter-than-air aircraft can be. Airship promises luxury air-travel that can last days in the skies, aiding unreachable disaster struck areas with ease or even search for extraterrestrial life. With further development in this sector it may not be long until the airships rise again.

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APPENDIX

The Longitudinal model

§ State space model for $U_0 = 25$ m / sec

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -0.0283 & -0.0434 & 10.3961 & 0.8266 \\ 0.0006 & -0.1807 & 31.2069 & -0.0102 \\ 0.0001 & 0.0031 & -1.0880 & -0.0860 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 0.0106 & 0.0000 \\ -0.0200 & 0.0000 \\ -0.0011 & 0.0000 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix}$$

Elevator response transfer functions,

$$\frac{u(s)}{\delta_e(s)} = \frac{N_{\delta_e}^{u}(s)}{\Delta(s)} = \frac{0.0106(s+0.0332)(s^2+0.2354s+0.0652)}{(s+0.0272)(s+1.1159)(s^2+0.1538s+0.0140)} \quad \frac{\text{m / s}}{\text{rad}}$$

$$\frac{w(s)}{\delta_e(s)} = \frac{N_{\delta_e}^{w}(s)}{\Delta(s)} = \frac{-0.0200(s+0.0273)(s+0.0308)(s+2.7723)}{(s+0.0272)(s+1.1159)(s^2+0.1538s+0.0140)} \quad \frac{\text{m / s}}{\text{rad}}$$

$$\frac{q(s)}{\delta_e(s)} = \frac{N_{\delta_e}^{q}(s)}{\Delta(s)} = \frac{-0.0011s(s+0.0272)(s+0.2374)}{(s+0.0272)(s+1.1159)(s^2+0.1538s+0.0140)} \quad \frac{\text{rad / s}}{\text{rad}}$$

$$\frac{\theta(s)}{\delta_e(s)} = \frac{N_{\delta_e}^{\theta}(s)}{\Delta(s)} = \frac{-0.0011(s+0.0272)(s+0.2374)}{(s+0.0272)(s+1.1159)(s^2+0.1538s+0.0140)} \quad \frac{\text{rad}}{\text{rad}}$$

Lateral Model

§ State space model for $U_0 = 25\ \text{m/sec}$

$$\begin{bmatrix}\dot{v}\\ \dot{p}\\ \dot{r}\\ \dot{\phi}\end{bmatrix} = \begin{bmatrix}0.0765 & -1.7072 & 10.1930 & -2.9511\\ 0.0408 & -0.3132 & 1.3723 & -0.5277\\ -0.0045 & -0.0048 & -1.1612 & -0.0058\\ 0 & 1 & 0 & 0\end{bmatrix}\begin{bmatrix}v\\ p\\ r\\ \phi\end{bmatrix} + \begin{bmatrix}0.0306\\ 0.0016\\ -0.0016\\ 0\end{bmatrix}\delta_r$$

Rudder response transfer functions,

$$\frac{v(s)}{\delta_r(s)} = \frac{N_{\delta_r}^{v}(s)}{\Delta(s)} = \frac{0.0306(s+0.7326)(s^2+0.1212s+0.4993)}{(s+0.1550)(s+1.1259)(s^2+0.1170s+0.5765)}\ \frac{\text{m/s}}{\text{rad}}$$

$$\frac{p(s)}{\delta_r(s)} = \frac{N_{\delta_r}^{p}(s)}{\Delta(s)} = \frac{0.0016s(s^2+0.5116s+0.4260)}{(s+0.1550)(s+1.1259)(s^2+0.1170s+0.5765)}\ \frac{\text{rad/s}}{\text{rad}}$$

$$\frac{r(s)}{\delta_r(s)} = \frac{N_{\delta_r}^{r}(s)}{\Delta(s)} = \frac{-0.0016(s+0.2019)(s^2+0.1270s+0.5765)}{(s+0.1550)(s+1.1259)(s^2+0.1170s+0.5765)}\ \frac{\text{rad/s}}{\text{rad}}$$

$$\frac{\phi(s)}{\delta_r(s)} = \frac{N_{\delta_r}^{\phi}(s)}{\Delta(s)} = \frac{0.0016(s^2+0.5116s+0.4260)}{(s+0.1550)(s+1.1259)(s^2+0.1170s+0.5765)}\ \frac{\text{rad}}{\text{rad}}$$

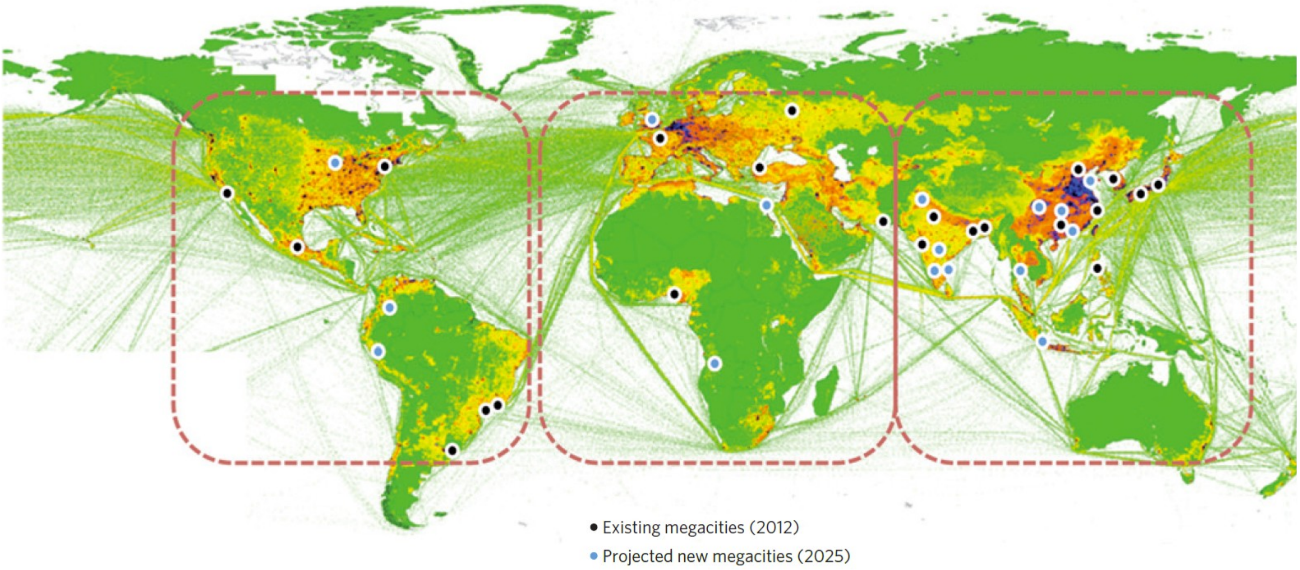

Figure 52 Megacity locations around the world for effective mobile platform coverage (Keck, 2014)

Solar Environment at 65 kft

Power to a stratospheric airship is supplied by the mounting of photovoltaic (PV) arrays within or on the surface of the airship. As such, the solar availability is of crucial importance to an airship. Figure 3.7 shows that the solar availability for a mid-latitude site (Washington DC) varies from ~9.5 hours in mid-winter to more than 14 hours in mid-summer, with a more extreme variation closer to the poles.

A portion of the energy gathered by the solar arrays is stored in rechargeable batteries or regenerative fuel cells to fuel night- time operation. Support circuitry is available to completely manage the charging and discharging. The battery control circuitry must be designed to eliminate the possibility of the energy storage system going off line unexpectedly as well as controlling charging rates, levels and power shedding.

Mounting of PV arrays on the hull surface introduces some inefficiencies due to the curvature of the hull thereby increasing overall system mass, requiring a larger airship. It also introduces large temperature variations due to the daytime heating of the arrays that the hull material must be thermally isolated from so as to not cause hull structural failure.

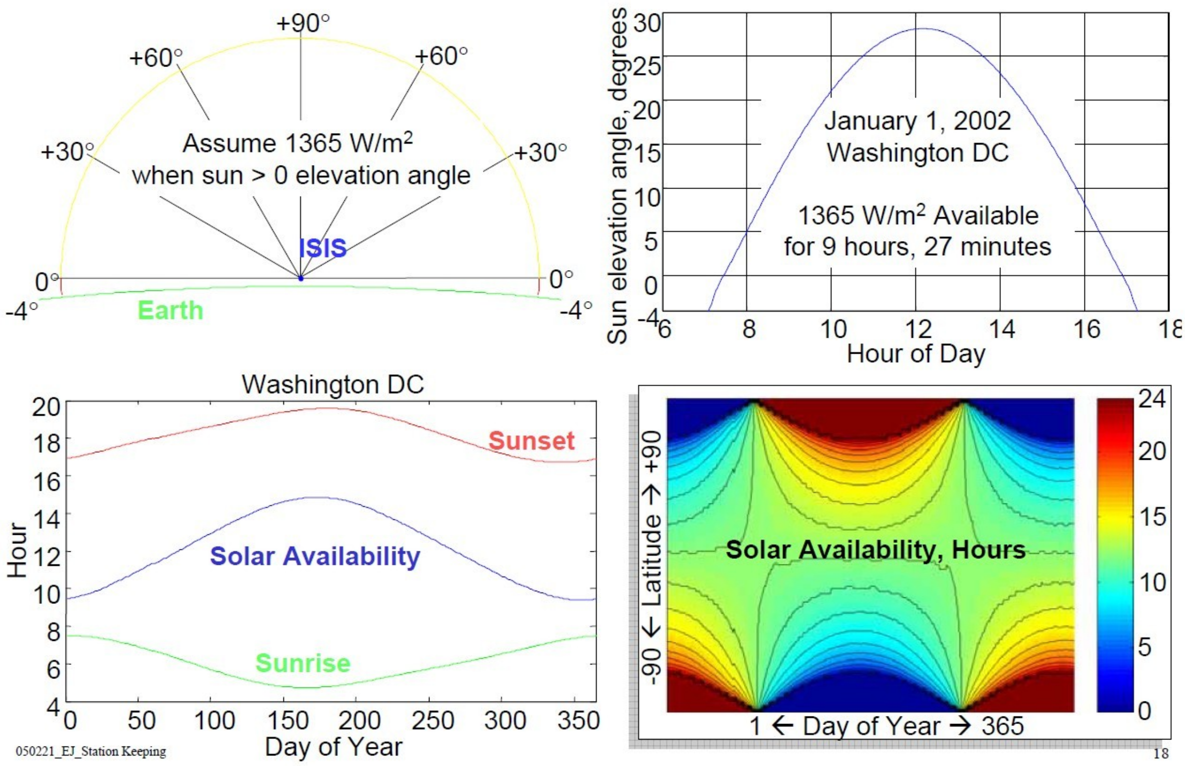

Figure 53 Solar availability for mid-latitude site, example shown is Washington DC. (Jaska, 2004)

The solar availability for a mid-latitude site, such as Washington DC, varies from ~9.5 hours in mid- winter to over 14 hours in mid-summer. (Jaska, 2004)

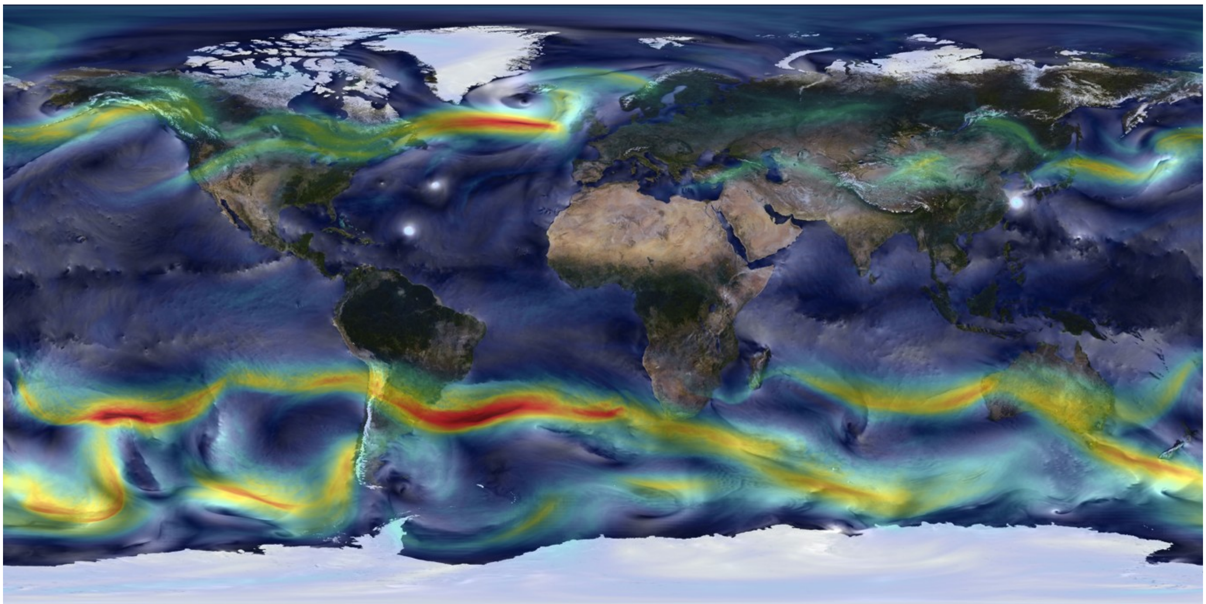

Figure 54 Global wind pattern for 2014 (NASA-Blue Marble, 2015)

MATLAB Codes:

```
%% Process using State SpaceRepresentation
TIME=100;
u=10*pi/180;% defines both \phi and \psi as the input of 1 degree
A = [ 0.0765 -1.7072 10.1930 -2.9511;
0.0408 -0.3132 1.3723 -0.5277;
-0.0045 -0.0048 -1.1612 -0.0058;
0 1 0 0];
B = [0.0306; 0.0016; -0.0016; 0];
C = eye(length(A));
D = zeros(4,1);
% t_sim2 = 0:1e-2:TIME;
t_sim = 0:1e-2:TIME;
%% Defining Impulse
u_sim_impulse= zeros(length(t_sim),2);
for m=(500:600)
u_sim_impulse(m,1)=u;
end % runns the first interval as the impulse of the aileron
for m=(2000:2100)
u_sim_impulse(m,2)=u;
end % runs the second interval of time as the impulse for the rudder
```

```
u_sim = u*ones(length(t_sim),1); % Step Input for SS
% [out_ss_im,t_ss_im] = lsim(ss(A,B,C,D),u_sim2_impulse,t_sim,[0; 0;
0; 0]);
[out_ss,t_ss] = lsim(ss(A,B,C,D),u_sim,t_sim,[0; 0; 0; 0]);
%% Plotting the State Space Representation
figure % will generate a brand new empty figure
subplot(4,1,1)
plot(t_sim',out_ss(:,1),'r-'),grid on; hold on
title('Step Input of Lateral Dynamics Using State Space, 10
Degree');
ylabel('V');
subplot(4,1,2)
plot(t_sim',out_ss(:,2),'b-'),ylabel('r'),grid on;
subplot(4,1,3)
plot(t_sim',out_ss(:,3),'g-'),ylabel('p'),grid on;
ylabel('p'); % labels the axii
subplot(4,1,4)
plot(t_sim',out_ss(:,4),'k-','Linewidth',1);grid on,hold off
xlabel('Time (sec)'); ylabel(',\theta');
clc
clear all
close all
%%
%% Process using State SpaceRepresentation
TIME=200;
u=1*pi/180;% defines both \phi and \psi as the input of 1 degree
A = [ -0.0283 0.0434 10.3961 0.8266;
0.0006 -0.1807 31.2069 -0.0102;
0.0001 0.0031 -1.0880 -0.0860;
0 0 1 0];
B = [0.0106 0.0000;
-0.02 0.0;
-0.0011 0.0;
```



```
 0 0];
C = eye(length(A));
D = zeros(4,2);
% t_sim2 = 0:1e-2:TIME;
 t_sim = 0:1e-2:TIME;
%% Defining Impulse
 u_sim_impulse= zeros(length(t_sim),2);
for  m=(500:600)
u_sim_impulse(m,1)=u;
```

```
end % runns the first interval as the impulse of the aileron
for  m=(2000:2100)
u_sim_impulse(m,2)=u;
end % runs the second interval of time as the impulse for the rudder
 u_sim = u*ones(length(t_sim),2); % Step Input for SS
% [out_ss_im,t_ss_im] = lsim(ss(A,B,C,D),u_sim2_impulse,t_sim,[0; 0;
0; 0]);
 [out_ss,t_ss] = lsim(ss(A,B,C,D),u_sim,t_sim,[0; 0; 0; 0]);
%% Plotting the State Space Representation
 figure % will generate a brand new empty figure
 subplot(4,1,1)
plot(t_sim',out_ss(:,1),'r-' ),grid on ; hold on
 title('Step Input of Longitudinal Dynamics Using State Space' );
ylabel('U' );
subplot(4,1,2)
plot(t_sim',out_ss(:,2),'b-' ),ylabel('W' ),grid on ;
subplot(4,1,3)
plot(t_sim',out_ss(:,3),'g-' ),ylabel('Q' ),grid on ;
ylabel('Q' ); % labels the axii
 subplot(4,1,4)
plot(t_sim',out_ss(:,4),'k-' ,'Linewidth' ,1);g
xlabel('Time (sec)' ); ylabel(',\theta' );
```