Design and Fabrication of a Portable Semi-Rigid Airship

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Abstract

This paper describes how a semi-rigid airship is designed and fabricated within specified dimensional limits. The design of Semi-rigid airship is crucial as it is dependent on numerous parameters such as structural weight, material, envelope shape, overall size, payload requirements, etc. Along with the functional parameters various other parameters are also considered, such as the portability of the structure, Envelope attachment to the structure, payload mounting, etc. are also considered. Along with that different tests, such as Helium Leak detection and making structural samples for checking strength, are performed so as to ensure that there is minimum variation in conceptual and actual design. The paper describes entire design and fabrication process followed to design a Semi-Rigid Airship as small as 4m in length which is capable of carrying a considerable amount of payload. The paper shows the process used for selecting a proper envelope shape and size according to design requirements. Rigid structure able to be dismantle is used as the structure of the airship. The weight of the structure is a critical parameter and hence various types of materials are considered. The paper not only gives an approach for design and fabrication, but also shows how the fabrication is carried out.

Keywords: *Lighter-Than-Air systems; Semi-rigid airships*

Introduction

An airship (or dirigible) is a powered, controllable, lighter-than-air aircraft. A predominant portion of lift in airships is obtained by the buoyancy of a lifting gas whose density is lower than that of ambient air. The highest lifting capacity per unit volume is for Hydrogen, which is also easily availability in large quantities, but is highly inflammable. Compared to Hydrogen, Helium has around 7% lower lifting capacity per volume [1], and is non flammable, but its availability is limited, and it much more expensive. The outer envelope of an airship may be formed from a single gas bag, or may be a separate supported skin. Besides the main envelope, an airship also has engines and crew and payload accommodation, typically in a gondola hung beneath the envelope.

Based on the structural configuration of the envelope, one can classify an airship as rigid, non-rigid, or semi-rigid. Rigid airships have a rigid structure mounted on an internal framework; hence they tend to be heavy. Non-rigid airships do not have any internal framework, and entire load is carried by the pressurized envelope itself. The semi-rigid configuration has a supporting structure (keel) that runs along the length of the airship, on which an envelope of flexible material is mounted, with or without any internal framework. There is still the need for a slight overpressure to maintain the envelope shape attached to the keel. The keel allows for a place to mount engines and fans such that the overall load is distributed along the entire airship. More or less integrally attached to the hull framework and/or the keel are the gondola, engines and sometimes the empennage. The framework has the task of distributing the suspension loads of these attachments and the lifting gas loads evenly throughout the entire hull's surface, which partially relieves the stresses on the hull during maneuvers. In early airships which relied on nets, fabric bands, or complicated systems of rope rigging to unite the lifting envelope with the other parts of the ship, semi-rigid construction was able to achieve improvements in weight, aerodynamics, and structural performance [2]. A semi-rigid Airship is generally smaller in size as compared to rigid airship for the same payload carrying capacity, but it may be larger than an equivalent non-rigid airship.

Most remotely controlled airships are of non-rigid type, due to ease in fabrication and transportability, and lower weight. However, in this configuration, the engines and payload can be installed only on a gondola that is generally mounted below the envelope. Further, the envelope design can be quite a problem, because it has to meet the dual requirement of gas retention, as well as handling all the loads acting on it.

A semi-rigid airship, on the other hand, provides more flexibility in location of payload and engines, since there is a rigid framework on which these can be directly mounted; this can result in higher maneuverability and better wind-disturbance handling capability. Once might be able to use a thinner (hence lighter) envelope material, since it is only supposed to meet the requirement of gas retention.

The presence of a rigid framework and keel in a semi-rigid airship can result in a heavier structure, and hence lower payload capacity, compared to a non-rigid airship of the same size. By careful selection of suitable material for envelope and structural framework, it might be possible for offsetting some of this disadvantage. Further, if the structure can designed to be quickly and easily dismantled, then the transportability of a semi-rigid airship can be greatly enhanced.

This paper describes a sizing methodology for a semi-rigid airship with a structural framework that can be quickly dismantled. The semi-rigid airship is designed and fabricated for the purpose of indoor demonstrations, which poses severe dimensional restrictions. As indoor demonstrations are planned to be carried out in a foyer or in an open hall, the typical dimensions of entry doors are considered as constraints on maximum width and height of the airship. The sizing of a semi-rigid airship is a function of numerous parameters such as envelope shape, weight of the structural framework, specific weight of envelope material, and payload requirements.

Various other parameters and issues, have to also be considered, e.g., the portability of the structure, envelope attachment to the structure, and payload mounting, to name a few.

In this paper, we describe the process followed for selecting a suitable envelope shape and sizing it according to the specified design requirements. A rigid framework which can be easily and quickly dismantled is used. The weight of the structure is a critical parameter, and hence various types of materials are considered. A three-dimensional CAD model of the structure is created, to check the dimensional interaction between the structure and the envelope. The model has also been used to estimate weight of various structural elements and fasteners, which helps in accurate determination of the payload carrying capacity of the airship. Apart from outlining the systematic approach followed for the design and sizing of a quick-dismantleable semi-rigid airship, the paper also describes the procedure followed for its fabrication.

Design Requirements

Based on the past experience of design, development and flight demonstrations of an indoor non-rigid airship [3], the following broad design requirements were finalized for this indoor airship:

- It should be possible to assemble/dis-assemble the structure of the airship within one man-hour.
- The nose of the airship should be attachable to the existing mast for indoor airships [4].

- Total length of Airship ≤ 4 m.
- Maximum width of the envelope ≤ 1.35 m

The constraints on the length and envelope width were arrived based on a survey of the dimensions of entry doors and demonstration space of several indoor auditorium and large classrooms.

Envelope

The envelope itself is the outer surface, usually surrounding one or more gas-bags and or ballonets within it. It is a gas containment member which encloses the lifting gas and provides protection from the environment.

For a semi-rigid airship, the envelope is one of the major structural elements, hence it deserves special attention. Materials, design and workmanship must be of the highest standard possible. Additionally, material performance and overall cost need consideration. Since these requirements are in some aspects contradictory, the challenge is to find the best compromise. The following standard envelope profiles were studied in order to decide the design specifications of the envelope:

- GNVR [5-6]
- Modified GNVR [7]
- Zhiyuan-1 [8]
- Custom shape (Sphere + Cylinder + Parabola)

CAD of Envelope

A scaled CAD model of the envelope was prepared in Auto Desk Inventor software, as shown in **Figure 1**. This model was further used for making the 3D assembly. The CAD model helps in understanding the relationship between the structural assembly and the envelope attachment.

Figure 1 : CAD model: envelope

Envelope Material selection and Sizing

Using the relation between various dimensional parameters and net lift, the most suitable shape and dimensions are chosen, and the GNVR shape was selected, as it resulted in the lowest surface area per unit volume.

The material of envelope is also an important factor to be decided as its characteristics greatly affects the overall performance of the Airship [9]. The following features are considered while selecting the envelope material:

- High Strength
- High Strength to weight ratio
- Low Permeability to LTA gas
- Low Creep
- Low Weight
- High Tear strength
- Good adhesiveness
- Resistance to environment degradation
- Good flexural and abrasion resistance
- Sealing ability

After a detailed market search and several experiments with various materials, a commercially available Low Density Plastic (LDP) was selected as the envelope material, to ensure low self-weight with adequate strength. LDP can be easily heat sealed and hence the envelope can be sealed in-house on Heat sealing machine, which reduces the fabrication cost and time. The values of key design parameters of the envelope are listed in **Table 1**, assuming pure Hydrogen as the lifting gas, and ISA Sea level conditions.

Frame

Semi-rigid airships have some characteristics of rigid airships and non-rigid airships. A rigid keel with an aerodynamic shape runs from nose to tail along the bottom surface of the air vehicle. In these airships, the keel supports the primary loads. This keel is used to eliminate the main function

Table 1: Key design parameters of the envelope

Parameter	Value
Profile	GNVR
Material	LDP of 70 gsm
Diameter	1.3 m
Volume	3.25 m^3
Surface Area	12.6 m^2
Envelope Weight	0.882 kg
Gross Lift	3.983 kg
Weight of LTA Gas	0.285 kg
Net Lift	2.816 kg

of the caternary curtain and evenly distributes the gondola weight along the airship's entire length. The interaction of keel and envelope may be partially favourable and partially unfavourable. The mutual support between the structure and envelope is good for resisting and distributing the bending moments between them while the poor fit of keel to envelope causes them to act against each other and generate additional stress. Thus, an accurate characterization of the interaction of envelope and keel and their mutual effects is a crucial consideration for semi-rigid airship design. It can be anticipated that semi-rigid airships have weights between those of non-rigid airships and rigid airships, since the keel on the bottom acts like a structural load bearing member.

Conceptual Design

Design is conceptualised based on the design requirement and it is decided to have a structure able to be dismantled, instead of a foldable structure, as it is more portable and suits the design requirements. It was decided to place the envelope inside the structural framework; to allow quick dismantling, and permit mounting of different equipment directly on the framework. Keeping the envelope outside the framework would also lead to complications and result in leakages at places where equipment and gondola is mounted. Also, having the structural framework visible from outside is also advantageous from demonstration point of view.

The structure consists of two circular and two semi-circular frames, on which several longerons and the nose hook are mounted.

Structural Joints

The joint of the structure, able to be dismantled was the most important part to be decided, as it has a significant impact on the portability of the structure. The joint was desired to be strong and light weight. Different types of joints were studied and accordingly, sandwich type joint was selected which is shown in **Figure 2**.

The joints on different parts of the structure is shown in **Figure 3**, where

Type a : Longeron to full ring

Type b : Longeron to half ring

Type c : Longeron to half ring

Typed : Longeron to Longeron (rear)

Figure 2 : CAD model: Sandwich joint

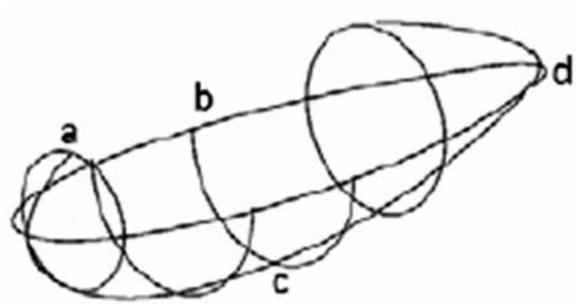

Figure 3 : Joints in semi-rigid airship

It was decided to use nuts and bolts for fastening purpose, as they are easily available, and are also easy to handle. Mild steel nuts and bolts do provide high strength, but are quite heavy. Hence, nylon nut bolts of 6 mm diameter were used, which are light weight and provide sufficient joint strength.

Material Selection for Structural Framework

Material selection for the semi-rigid structure was the most critical step to be taken, to ensure adequate strength and other structural properties, without too much increase in weight. The semi-rigid structure is expected to serve as a framework for rigidly attaching the envelope to it. Apart from the envelope, it must be capable of carrying power plant, batteries, radio receiver and nose hook for attaching it to the mooring mast. Various materials were short listed and tested, as described in the sub-sections that follow.

Jute Reinforced Plastic (JRP) Rods

JRP is a composite with a combination of Jute and a plastic polymer **(Figure 4)**. Jute is easily available and is economical which makes these rods affordable, as compared to carbon fiber rods. JRP rods can be easily bent, but they lack the capability of retaining the bent profile. JRP has a high spring back and thus is unable to maintain the given profile. The density of Jute fiber reinforced plastic is found to be around 540 kg/m^3.

Jute Reinforced Plastic (JRP) Plate

This material is similar to JRP rods, but it is in a plate form. A flat plate can be machined to get required profile using laser cutting or milling. Such a precise machining process guarantees to get desired profile. The density of the plate was found to be 790 kg/m^3.

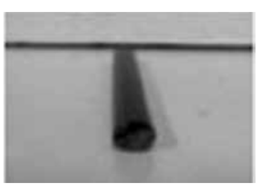

Figure 4 : Jute reinforced plastic rod

Balsa

It is a well-known light weight material used for aeromodelling **(Figure 5)**. A desired profile was obtained by laser cutting the balsa sheets and strength testing was carried out. It was found that even though balsa has excellent in-plane strength, it has very poor out-of-plane strength. Thus it was decided to avoid using Balsa for Longerons. Apart from this, the unavailability of large Balsa sheets also posed additional restrictions.

Carbon Fiber Reinforced Balsa (CFRB)

Carbon Fiber is well known for its high tensile strength and low weight **(Figure 6)**. CFRB has a similar weight, but has significantly lower cost. A sample was made using resin (LY 556) and hardener (HY 951). Parameters such as weight, density, manufacturability and strength were tested. It was found that it had a density of 472 kg/m^3 and had adequate strength.

Carbon Fiber Reinforced Polyurethane (CFRPU) Foam

PU foam is Polyurethane foam which has properties similar to that of thermocol **(Figure 7)**. But it has lower strength than required and hence CFRPU is considered which gives an added advantage of increase in strength. The density of this composite is found to be around 290 kg/m^3.

Carbon Fiber Reinforced Depron (CFRD)

Depron™ is extruded polystyrene foam which has

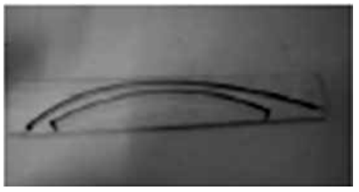

Figure 5 : Balsa

Figure 6 : Carbon fiber reinforced Balsa

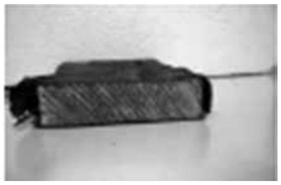

Figure 7 : Carbon fiber reinforced PU foam

Figure 8 : Carbon fiber reinforced Depron

low density, but it has low out of plane strength **(Figure 8)**. If it is reinforced with a composite carbon fiber, this shortcoming is removed. CFRD has a better strength as compared to Depron™ and has lower cost as compared to CFRs. The density is found to be 300 kg/m^3.

Material Selection

From all the above alternatives, CFRPU foam was shortlisted as the material for the structural framework, due to following reasons:

- PU Foam, of desired shape and size, is easily available. Balsa is available only in small sizes which make it impossible to be used.
- It is available at low cost (Rs. 95 per sheet) as compared to that of JRP or Balsa.
- The Resin and Hardener required for bonding of composite is easily available.
- CFRPU foam can be machined to get desired profile which is not the case with carbon fiber alone, as it is quite difficult to machine carbon fibre.
- It has higher strength compared to Depron™, PU foam or Balsa.

Nose and Tail Attachment

A nose batten is provided in airships, to facilitate its attachment to the mooring mast. A nose hook is provided for this airship with a view to facilitate ease in assembly and disassembly of the structure. Four extended hollow portions are provided which accommodate the four Longerons. Holes are provided so that the Longerons can be bolted to the nose hook. The nose hook has a cylindrical projection at the front, which is used for attachment with the mooring mast. Tail hook is designed on the similar lines, so as to accommodate the Longerons. Holes are provided on both Nose and Tail so as to bolt the Longerons. Both nose- and tail hooks are expected to have adequate strength and should be capable of performing their function along with least possible weight. It was decided to go for 3D printing of these parts in ABS plastic. **Figures 9a and 9b** shows the CAD models for the nose- and tail hook, respectively.

Detailed CAD Model

After finalising the geometry of the structure and material selection, a detailed CAD model was made in AUTODESK Inventor™, as shown in **Figure 10**.

The CAD model provided a base to estimate the quantity of material required for the structure, and

(a) (b)

Figure 9 : CAD for nose and tail hook

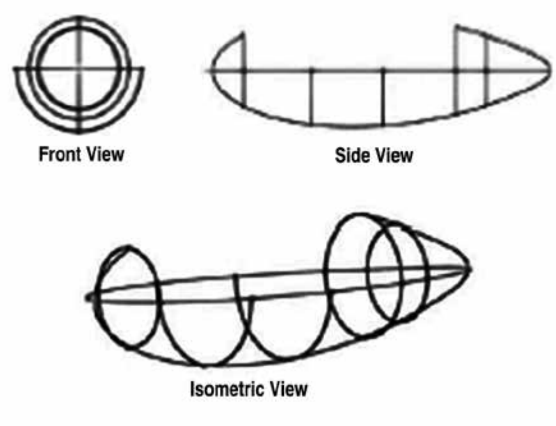

Figure 10 : 3D structural assembly

also gave a rough estimate of the weight of the semi-rigid structure.

Joint and Fasteners

The design of structural joints was a crucial part of this study. It was essential to select a joint keeping in mind the need of a quick dismantle-able structure of the airship. It was decided to go with a sandwich type of joint, and use plastic Nuts and Bolts of 6 mm diameter as fasteners, for ease in assembly and disassembly, and low weight. A total of 32 fasteners were needed due to the long length of the airship. The plastic nut bolts provided adequate joint strength along with significant weight reduction.

Fabrication And Assembly

Composite Material Fabrication

First the composite material was made using Carbon Fibre mat, PU foam sheet and Resin and hardener mixture. The Resin and hardener was mixed in the ratio of 10:1. The mixture was applied on PU sheet and then it was wrapped with the carbon fibre mat. The composite was then soaked for 24 hours, after which it was ready for further machining. One needs to take proper care while using Araldite as adhesive. The resin hardener mixture starts to have an exothermic reaction and the adhesive loses its flow-ability. In such a case, it becomes difficult to apply the adhesive on PU sheets. To avoid this, the adhesive was applied as soon as the resin and hardener are mixed together. The composite sheets were adequately cured before machining.

Profile Cutting

A carbon fibre with mixture of resin and hardener forms a very strong bond and ultimately a strong composite. Laser cutting had virtually no effect on the composite and hence profile cutting using water jet machining was considered. The water jet machining gives a fine profile cutting. Few samples were machined for initial testing of strength. **Figure 11** shows photographs of some results of profile cutting.

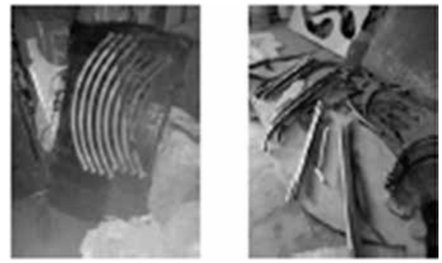

Figure 11 : Profiles cutting for longeron

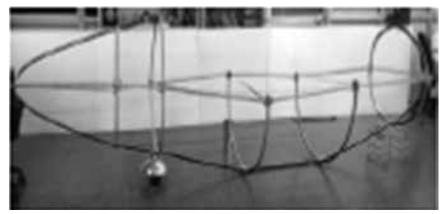

Figure 12 : Structural assembly

Structural Assembly

The Profiles were then prepared for assembly. Sandwich type of joint was used for assembly. For this, a transverse extruded joint was glued at the ends of the profile, using Araldite. The assembly was started from the nose end and was finished at tail end. The 3D printed Nose hook was used as a start point for assembling the structure, which eliminated the need for aligning the front longerons relative to each other. After the front longerons, first full ring was attached using Nylon nuts and bolts. The full ring was then used as a support for assembling the further longerons and other rings and semi rings. The structure alone without envelope is not capable of standing by itself. Hence it is supported on its sides by using various supports, as shown in **Figure 12**. Also a ribbon is used to tie two semi rings and to tie the front part with the rear part to avoid sagging.

Envelope Sealing

Envelope sealing is a very important and a crucial part of the semi rigid airship. Heat sealing machine was used for envelope sealing. Proper care was taken while deciding the temperature and holding time of the sealing machine. The envelope was made of eight identical petals, which were created using the methodology explained in [3]. The petals are sealed together properly, and special care was taken at the ends of the envelope. The envelope ends have a high tendency of leakage. All the petals are sealed properly and was then inflated using an air Compressor. The air inflation was important as it gives an overall idea of volume and leakages present in the sealed Envelope. All the visible leakages are sealed and then, leak detection test was performed. A fabricated airship envelope is shown in **Figure 13**.

Helium Leak Detection Test

The envelope generally has some leakages associated with it, due to imperfections while heat sealing the edges. Helium leak detection test is performed so as to determine the locations of these leakages in the envelope. A small volume of Helium is filled in the envelope, and then the remaining volume is filled with air. A Sniffer probe, connected to the leak detector, is moved along the envelope surface, so as to detect all the possible leakages. The detected leakages were sealed using sealing tape and again a leak detection test was performed.

Structure and Envelope Assembly

The structure was assembled starting from the nose hook to the tail hook, and was kept supported before attaching the envelope to it. The Longerons are first inserted into the nose hook and their other ends were attached to the circular frame. Similarly, all other set of Longerons were assembled and the last set was attached with the help of tail hook. The envelope was then inserted inside the structure and was attached at ten different points on the structure. The Envelope was then inflated with lifting gas and the assembly was ready for further testing and trials. The assembly of semi-rigid airship is shown in **Figure 14**.

Figure 13 : Fabricated airship envelope

Figure 14 : Assembly of semi-rigid airship

Conclusions

This paper described the design methodology and fabrication procedure of a dismantleable semi rigid airship. The design phase involved review of various shapes and configurations. The most suitable design was chosen through systematic comparisons of possible alternatives. A large variety of materials were considered for the airship structure. Different composite materials were prepared in-house and their samples were tested. The keel-frame was designed to be dismantleable and light-weight. Finally, the entire envelope and frame were fabricated and assembled for flight-testing.

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References

1. E. Moforth, “Basic Principles” In Airship Technology, Khoury G. A., ed., pp.8-15, Vol. 2, Cambridge University Press, 2012.
2. L. Liao and I. Pasternak, “A review of airship structural research and development,” Progress in Aerospace Sciences, vol. 45, pp. 83-96, May-July 2009.
3. G. Bansal, U. Bhardwaj, N. Jain, S. Mulay, S. Sawardekar and R. S. Pant, “Design Fabrication and Flight testing of a Non-rigid Indoor Airship”, AIAA-2013-1297, Proceedings of 20th AIAA LTA Systems Technology Conference, 25-27 March 2013, Daytona Beach, FL, USA.

4. K. Syed, U. Bhardwaj, and R. S. Pant, "Design, Fabrication and Testing of Mooring Masts for remotely Controlled Indoor and Outdoor airships", Journal of the Institution of Engineers (India): Series C, Mechanical, Production, Aerospace and Marine Engineering, Springer, ISSN: 2250-0545, 2014.

5. S. Sundaram, "Wind Tunnel Tests on 1:7 and 1:28 scale Aerostat models," Technical Report, Experimental Aerodynamics Division, NAL, Bangalore, India, 2000.

6. C. Narayana and K. Srilatha, "Analysis of aerostat configurations by panel methods," BLISS project Document CF 0010, NAL, Bangalore, India, 2000.

7. R. Joshi, A. Raina and R. Pant, "Conceptual Design of an Airship using Knowledge Based Engineering," AIAA-2009-2861, Proceedings of 18th AIAA Lighter-Than-Air Systems Technology Conference, Seattle, Washington, USA, 4–7 May 2009

8. X. Wang, G. Fu, D. Duan and X. Shan, "Experimental Investigations on Aerodynamic Characteristics of the ZHIYUAN-1 Airship," Journal of Aircraft, vol. 47, pp. 1463-1468, 2010.

9. T. Miller and M. Mandel, "Airship Envelopes: Requirements, Materials and Test Methods"