Paper 2004-01 - Design Studies of Power Plant System of Non-Rigid Airships

Amol C. Gawale[1], Rajkumar S. Pant[2]

Aerospace Engineering Department
Indian Institute of Technology Bombay, Mumbai- 400076

Abstract:

Power plant is of prime concern in the engineering design of a Non-Rigid airship. Such airships usually operate with a gondola-mounted ducted propulsive system. This paper provides an overview of the power plant system, design issues in engine sizing and selection, advances in engine technology, various concepts for thrust vectoring and a methodology for sizing and selection of design features of an airship engine.

Introduction:

Airships are Lighter-Than-Air aircraft, which generate lift due to buoyancy of the lifting gas. The lift is produced by the net density difference between the ambient air and a lighter-than-air gas (which, in most cases is Helium) that is confined in a calculated space by means of a bag like non-rigid structure called Envelope. The net disposable lift (i.e. the gross lift generated minus the empty weight of the airship) can be utilized as payload to carry Passengers or cargo. Airships may sound a bit old-fashioned, but the non-rigid lighter than air vessel is a state of the art surveillance platform. It can float for days at a time carrying on radar surveillance, and is ideal for accompanying a naval task force. Airships are being gainfully employed all over the world for multifarious applications including product promotion, specialty tourism, aerial photography & surveillance, wild life tracking, Cargo transportation, and also in several military roles.

Conceptual design of the power plant for non-rigid Airship is affected by many parameters. Its sizing is primarily driven by the desired performance parameter such as max. speed, operating altitude, range and endurance. However, power plant design is also affected by several features and requirements such as engine location, symmetry of the thrust, noise level, noise isolation, vibration isolation, mechanisms for engine control, and fuel tank location. Aesthetics and Ergonomics also play a very important part in the design process, and lead to several compromises in the design.

Design issues in engine sizing and selection:

Some important issues that affect the sizing and selection of the engine for an airship are as follows:

Max. 'In Flight' fuel usage

Based on the region of operation, range and onboard power requirements, the maximum 'in flight' fuel usage can be worked out with ease and accuracy. This 'in flight' fuel usage is limited by the two extremities viz. *Takeoff Heaviness* and *Landing Lightness*; former is the airship mass greater than the static equilibrium and latter is airship mass lower than static equilibrium. For a multi-engined airship, Takeoff Heaviness is limited by the ability of the airship to climb to an altitude of 50 feet without any loss of height at any point in the flight path, following an engine failure at the critical point. Landing Lightness is limited to a point at which the airship ceases to be easily controllable during landing by an average ability pilot.

As an airship continues its operation, the onboard fuel continues to burn, as a result, the airship becomes somewhat lighter; and its weight could sometimes go beyond the equilibrium. For this reason a proper

---

[1] *Project Engineer*
[2] *Associate Professor*

mechanism has to be developed for maintaining the airship weight with minimum oscillations about the static equilibrium.

Hunt has suggested that the weight lost in terms of fuel used during flight can be compensated using the following methods [1]:

1) On-board ballast recovery systems:
In this method, the water vapor present in the engine exhaust is recovered and stored on-board, or the moisture present in the ambient atmospheres is condensed and collected. This method leads to additional cost and complexity, increase in power consumption, and airship empty weight.

2) Ballasting with water:
In this method, the airship is brought down, and the weight lost due to consumption of fuel is replenished by an intake of equivalent amount of water. This method seams to be applicable only while flying over the ocean, river or a water body. A great skill is expected from the pilot while doing such maneuvers because as an airship is made to fly low, its structure (especially the envelope) will be prone to higher stresses due to the presence of gusts and turbulence disturbances, which can cause structural damage.

3) Dumping Helium:
In this method, the equivalent weight lost in terms of fuel used is compensated by releasing Helium. However, this method leads to a substantial increase in operating cost, since Helium is a very expensive and rare source, hence it should be only as the last resort, such as during emergencies.

Innovative efforts towards development of efficient ballast recovery systems using Solar, Fuel cells and/or battery powered airships will probably provide a lasting solution to this problem. Fig. 1 explains the maximum in-flight fuel usage, as discussed above.

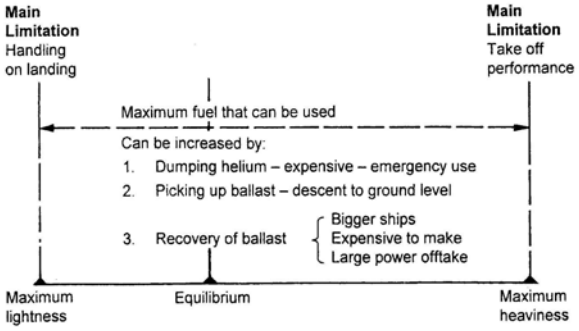

Fig. 1: Maximum in-flight fuel usage

Engine Selection

The range of propulsive power required for level flight in an airship is far greater than that in Heavier-Than-Air (H-T-A) aircraft. This presents problems in selection of a suitable engine for an airship. Specific fuel consumptions quoted by engine manufacturers are based on H-T-A requirements, where, except in circum-stances such as power-off descents, 'in flight' power is usually in excess of 50 % of take off power. Normally, manufacturers quote the SFC for either max. cruise, max. continuous or for take-off power (TOP). MCP will normally be at least 80% of the TOP. Fig. 2 shows the SFC variation with % engine power for various aircraft types.

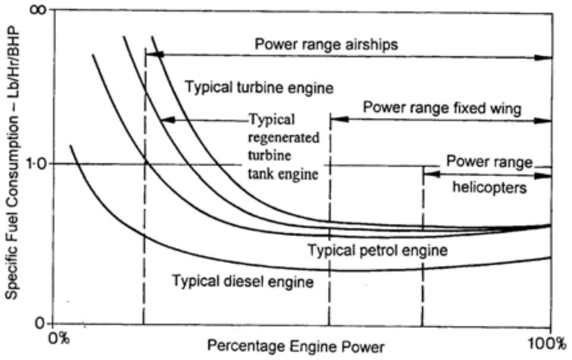

Fig. 2: SFC for different aero engines and their application for various airborne vehicles

It can be seen that there is little difference at these two ratings and relatively small differences over the full power range for H-T-A machines.

Airships operate at take-off power settings for very short periods (typically 30 seconds), in order to obtain short field lengths and high take off heaviness, and cruise at much lower percentage powers.

A typical power on a small airship cruising at about 55 kmph could be less than 20 % of the TOP. At this low power, SFC for all engines are higher especially for turbines where they may be up to over four times that either TOP or MCP. The poor SFC of turbines at lower power is possibly explained by their self-sustaining ground idle fuel flow. One of the most popular small turbines has the fuel flow at ground idle (zero horsepower) of 34 kg/hr/eng. A similar sized piston engine equipped, small airship could be cruising at in excess of 64 kmph with this total ship fuel flow.

For short duration flights, there may be advantages in using turbines. This is because of their lighter installation weight compared with currently certified piston engines (it may be possible to mount them outboard and vector them if their oil system allows). However the flight duration at which the turbine-powered ship becomes less attractive than one powered by reciprocating engines, becomes lower as cruise speed increases. This is because the higher fuel flow of the turbine-powered ship will cancel the advantage of their lighter installation weight of the engine above this duration. The duration at which this happens can be determined by constructing a chart shown in Fig. 3 for the size of the airship and power plants being considered.

This chart should be calculated for all the engines. If no form of ballast recovery is fitted, the amount of fuel used (including reserves and ballast that may be dumped) must not exceed the difference between maximum heaviness and maximum lightness in normal use.

Further, the choice of the engine type is also influenced by the total operating cost i.e., initial cost, running cost in terms of maintenance expenses and fuel as well as the effect of the weight on payload to be carried.

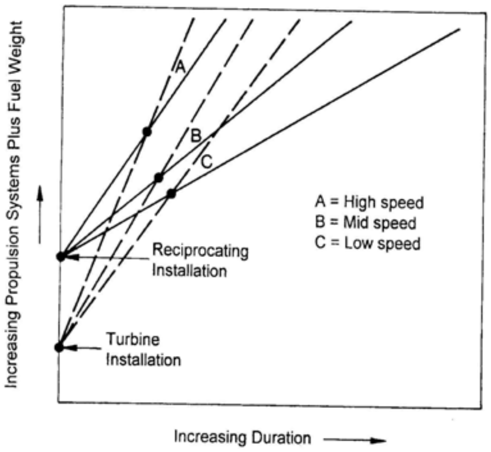

Fig. 3: Propulsion system weight +fuel weight Vs duration for two different engine types

Power off-take

Electrical power demand to drive systems such as air conditioning in passenger airships, or missions fit for military operations, tends to be much greater now than in previous years. Because of the very low power required to propel the airship, systems consume a much higher percentage of the total power required than on H-T-A-aircraft.

Compared with an H-T-A aircraft (requiring 5 to 15 % of the total engine power to drive the electronics), on some of the military systems that have been investigated in the airship role, the electrical power required has been well over 65% of the total power required at low medium cruise speeds. This means that the fuel used to generate the electrical power requirement may be considerably greater driver in determining the duration of the ship than the propulsive power required as they are both included as parts of the maximum ‘in flight’ fuel usage.

It follows that much care must be taken in deciding how this power should be taircraft APUs are invariably powered by small turbines with poor SFCs (by L-T-A standards) and are mainly producers of large quantities of air rather than electrical power the airship requires. Piston powered APUs driving electrical generators usually require developing for the specific application, normally at very high cost. If possible, the best solution is to drive generators from the propulsion engines which invariably give the lowest SFC (and installed weight) and hence fuel usage- but depending on the types of engines used, matching of engine/ generator RPM ranges may cause problems. Also, depending on the electrical power required during the take-off phase, it may require a rework of the take-off power required.

Engine Drives and propellers

While taking decision on the engine-propeller combination, care has to be taken to obtain the propeller efficiency as high as possible and also thrust vectoring should be possibly an option in any case. Many mechanisms are possible for the engine and propeller combination viz.,

1. Engine mounted within the gondola, and propellers driven by means of the belt drives with reduced RPM. This arrangement can result in propeller efficiencies up to 70% at normal airship cruising speeds, unless very large slow turning propellers are used.
2. Propeller directly coupled to the engine without and reduction gear box outside the gondola or to the envelope. The efficiency will be in the range of 50-55 % in the cruise segment [1]. This is because their design is not set to moderate RPMs as required for airship cruising speeds. Installed efficiencies are much lower than the values quoted by propeller manufacturers, due to the problems in matching the performance with engine output RPMs.

Higher propeller efficiency will be possible if engine, propeller and airship manufacturers work in coordination for design of a specific airship engine.

Advances in Engine Technology:

Fuel and its availability is the first thing to be worked out the before selection of the engine type. In many areas of the world today, availability of petrol for aviation applications is still vary scarce. Hence, petrol engines will not be a good choice for airships meant to operate in such areas. It is reported that two-stroke diesel technology will eventually find an application in airship technology [5]. With little modification, Diesel engine's ability to run on anything from diesel through to kerosene allows it to be operated virtually anywhere. There are exciting prospects for the two-stroke diesel engine in Aviation; some manufacturers have modular two-stroke diesel engine range; configurations include V-twin, Radial 4 and Radial 8 cylinder with high degree of compactness and minimum number of the parts, producing good power and retaining full aerobatic capability. A supercharged two-stroke diesel also has none of the lubricant/intake air contamination problems that lead to the exhaust like smoky, smelly petrol two-stoke engine. Dry sump pressure lubrications, with the clean air used for scavenge going directly into the cylinders, not via the crankcase is a milestone in Diesel Design evolution. Using direct injection, the engine breathes through piston ports for both inlet and exhaust, so there are no poppet valves, camshaft or valve gear. Modern diesel engine has some unique features to combat inherent piston engine imbalances and reduce vibration. Requiring minimal counterbalance and contributing to the engine's low weight. Diesel engines can be made to run at propeller speed so that it does not require reduction gearboxes and right-angle drives of the existing airship engines. This leads to better performance and higher propeller efficiency and hence further weight reduction.

Thrust Vectoring System:

During in-flight operation an airship requires some maneuverability in terms of pitching and turning, to tackle some difficult operational scenarios. Also, while taking off, the complete thrust arising from the engine driven propeller has to be directed downward. Thrust vectoring systems are required to achieve this. Based on the weight of the propulsion system, thrust vectoring system weight is 0.12 to 0.16 kg per kg of vectored mass of air, which is only a small part (4% to 6%) of the whole propulsion system weight as stated by Craig in [1]

The two configurations for providing thrust vectoring are possible, viz.:

1. Combined Ducted propeller-engine Thrust vectoring system: - The complete thrust system comprising engine, propeller and duct collectively rotated as desired. In this type, efforts required are more due to addition of gyroscopic torque. Also, because of increased torsional moments while rotating, required load bearing members gets increased leading to additional gondola weight. Thus engines can not be put little away from the gondola so as to have minimal noise and vibrations. Despite of all these effects, system is quite simple to realize and can be worked out for small airships.
2. Multiple louver vane system: - This system basically consists of circular duct over the propeller which is then lofted in square/rectangular shape. At this end, some louver shaped vanes are attached in a circular fashion as shown in the Fig. 4.

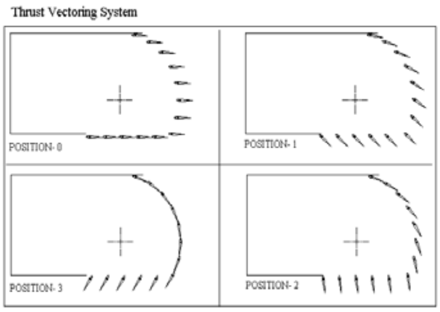

Fig. 4 Louver profile vane thrust vectoring system

Some vanes may be attached at the bottom of the duct too. Now, when the airship takes- off, the total thrust is diverted towards bottom by adjusting the angles of the vanes, as shown in Position three in Fig. 4. The desired position of the vanes when the airship is in Cruise mode is also shown in Fig. 4.

Provision can be made to position the louvers at any desired intermediate position also, allowing any desired split between upward and forward components of the thrust forces. Lofting of the cross section from circular to square or rectangular is required for achieving minimum fabricating cost by making identical louver vanes.

Since undesirable gyroscopic torque is removed, as there is no rotation of engine-propeller-Duct system, lesser effort is required to move all vanes simultaneously through their respective angular displacements. Also there is no need to provide more members for load bearing, thus leading to minimum weight of the gondola. This is a suitable option from reliability, thrust recovery and ease of manufacturing and for effortless operation.

However, to use such a configuration as a thrust vectoring system, some experimentation has to be carried out so as to obtain the data about the performance of the whole configuration to obtain the net thrust and normal force available from the engine + propeller + thrust vectoring louver system for various louver angles.

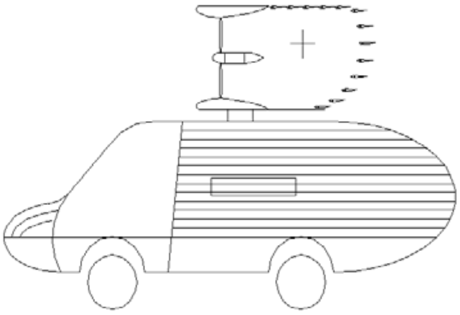

Fig. 5: Set up for validating thrust vectoring system

A conceptual sketch illustrating the set up for validating the thrust vectoring system by mounting it on a streamlined vehicle is shown above in Fig. 5.

This vehicle can be suitably instrumented, and force, torque and fuel flow measurement can be carried out by running it at a uniform speed on a smooth road or level test tracks. Alternatively, the above studies could be carried out by mounting the power plant assembly in an Open-Jet wind tunnel.

Methodology for sizing and selection of an airship engine:

A methodology for arriving at the baseline specifications of a non-rigid airship of conventional configuration, given the performance and operational requirements has been developed as part of the ongoing Program on Airship Design & Development (PADD) at IIT, Bombay. This methodology uses statistical data related to existing airships, and arrives at the geometric parameters based on empirical and semi-empirical equations, most of which were taken from standard design textbooks such as Khoury & Gillett [1], Raymer [3] and Stinton [4]. The methodology calculates the power requirements based on the operational inputs such as Range, Cruising speed and altitude, Pressure Height and Atmospheric conditions. The details of the methodology are reported in [2], due to paucity of space. The selection of a particular power-plant related design feature or option as listed in Table 1 has a direct effect on some of the parameter values, as discussed below.

Design Feature	**Option 1**	**Option 2**
Engine Type	Diesel	Petrol
Engine Charging	Normally aspirated	Supercharged
Propeller Type	Ducted	Un-ducted
Thrust Vectoring	Present	Absent
Transmission system	Simple	Complex

Table 1: The optimal design features for initial sizing of the power plant

Effect of power plant related design features and options:

The choice of engine type (Diesel or Petrol) affects the engine specific fuel consumption and weight per unit power. These parameters were taken as 0.46 lb/(HP-hr) and 0.85 kg/HP for Petrol engines and 0.37 lb/(HP-hr) and 1.025 kg/HP for Diesel engines, respectively, which are the average of the values suggested by Cheeseman in [1].

The choice of normally aspirated v/s supercharged engine affects the value of the power lapse factor with altitude, which, for normally aspirated piston-prop engines was estimated using the formula in Eq. 1 suggested by Raymer [3]. For supercharged engines, k_{alt} is assumed to be unity.

$$k_{alt} = \sigma_{crH} - \left(\frac{(1 - \sigma_{crH})}{7.55} \right) \qquad (1)$$

Where, $k_{alt,}$ s_{crH} are lapse factor with altitude and air density at cruising altitude. The use of ducted propeller leads to improved propeller efficiency lower noise levels and higher operational safety near ground, at the cost of increase in weight and complexity. Stinton [4] has plotted the variation in propeller efficiency of propellers and ducted fans with airspeed. The mean values of propeller efficiency for un-ducted and ducted fan in the speed range of 70 to 90 kmph were taken as 0.53 and 0.76, respectively. The weight of the un-ducted propeller, ducted propeller and the duct was taken as 0.175, 0.125 and 0.375 kg /HP, respectively, which are the mean of the range for these values suggested by Craig in [1].

Provision of thrust vectoring leads to an additional weight penalty, which is estimated as 14% of the weight of the vectored mass. This value is the mean of the range suggested by Craig in [1].

A simple transmission system with no separate accessory gearbox was assumed to weigh 0.17 kg/HP installed power. On the other hand, a complex system including accessory drives was assumed to weigh 0.275 kg/HP of installed power. These figures are the mean of the ranges suggested by Craig in [1] for an inboard engine and outboard propeller configuration.

This methodology was applied to carry out conceptual design studies of two airships, viz. *Demo* airship and *PaxCargo* airship. *Demo* airship is capable of operating with a payload of around 100 kg under hot and high conditions in mountainous regions at a cruise altitude of 3500 m at ISA +15^0 C, while the *PaxCargo* airship has a payload capacity of 1500 kg under the same operating conditions. Three view diagrams of *Demo* and *PaxCargo* airships are shown in Fig. 6 and Fig. 7, respectively.

Based on the knowledge gained during the literature survey and study, the methodology provides the baseline specifications for the suitable engine for the airships. With this knowledge, a large amount of information about different kinds of such engines has been collected and collated. A classification has been done for these engines based on its SHP in the increasing order. Table 2 and Table 3 list some parameters related to the engines for *Demo* and *PaxCargo* airships, respectively. As more space was required for representing these two tables, they are shown after the references.

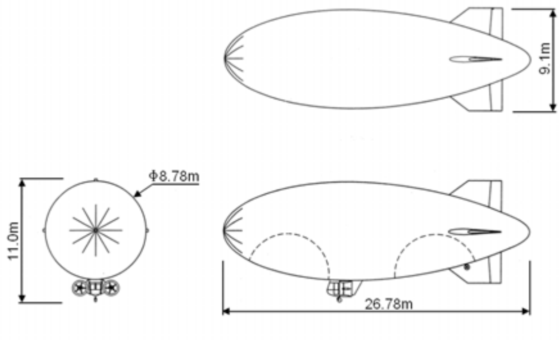

Fig. 6: Three views of Demo Airship

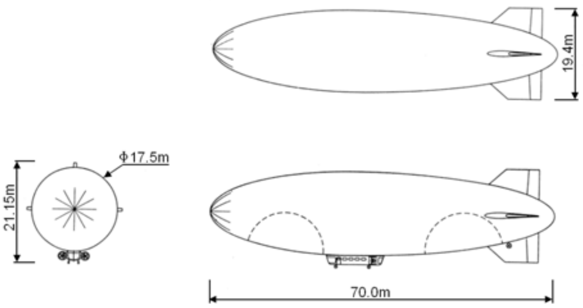

Fig. 7: Three views of PaxCargo Airship

References:

[1] Khoury G. A., and Gillettt, J. D., Eds., *“Airship Technology”*, Cambridge Aerospace Series: 10, ISBN 0-521-430-747, Cambridge University Press, 1999

[2] Pant R. S., *“A Methodology for Determination of Baseline Specifications of A Non-Rigid Airship”*, 3rd Annual Aviation Technology, Integration, & Operations (ATIO) Forum, AIAA, Denver, Colorado, USA, 2003

[3] Raymer D. P., *“Aircraft Design: A Conceptual Approach”*, AIAA Education series, AIAA, Washington D.C., USA, 1989.

[4] Stinton D., *"The Design of The Aeroplane”*, Blackwell Science Limited, UK, ISBN 0-632-01877-1, 1995.

[5] *"Lighter than Air"*, Diesel Car Magazine, Germany, Nov. 1994

Engine Type	**Weight (Dry)**	**Max. Power**		**Arrangement**	**Cooling**
	kg	**kW**	**HP**		
NOVIKO DN-200	105	110	148	6 cylinder, horizontally opposed, 2 strokes, diesel	Liquid
ZOCHE ZOD1A	84	110	150	4 cylinder in X configuration, 2 stroke diesel	Air
WANKEL ROTARY TWIN PACK	119	110	148	4 rotor wankel diesel engine	Liquid
VAZ 426	125	110	148	2 rotor wankel diesel engine	Liquid

Table 2: Candidate engines for Demo Airships

Engine Type	**Weight Dry**	**Max. Power**		**Max. Rpm**	**Arrangement**	**Cooling**
	kg	**kW**	**HP**			
HIRTH F31	26.5	29.1	39.0		2 stroke 2 cyl., horizontally opposed	Air
HIRTH 2702	31.0	29.8	40.0	5500	2 stroke 2 cylinder in line	Air
HIRTH 2701	32.8	32.1	43.0		2 stroke 2 cylinder in line	Air
ROTAX 447UL-IV	26.8	29.8	40.0	6800	2 stroke 2 cylinder in line	Air
ROTAX 447UL-2V	26.8	31.3	42.0	6800	2 stroke 2 cylinder in line	Air
UAV AR 731 *	10.0	27.6	37.0	7800	1 rotor wankel-type spark ignition	Air
UAV AR 741	10.7	50.0?	67.0 ?	7800	1 rotor wankel-type spark ignition	Air assisted by centrifugal fan
WANKEL ROTARY LCR 407 SGTI	25.0	27.2	36.4		1 rotor wankel diesel	Liquid
WANKEL ROTARY LCR 407 SD	38.0	33.1	44.4		1 rotor wankel diesel	Liquid
VRDE RE-4-37-P	22.0	27.6	37.0	5500	2 stroke 4 cyl., horizontally opposed	Air

Table 3: Candidate engines for PaxCargo airship