The Potential of Buoyant Aircraft for Passenger Transport

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ABSTRACT

The idea of using buoyant travel for short-to-medium range scheduled passenger services gained some impetus in the 1960s, partly in response to noise and other problems arising with then-existing passenger helicopter services. The late 1990s saw a revival of interest in buoyant aircraft. A variety of proposals were put forward and, although some again failed, others continue and are at prototype stage.   The paper looks at recent developments in this area with a view to identifying the most promising type of craft for potential use in passenger travel.

INTRODUCTION

Buoyant air transport is defined as any air-based system where the vehicle is supported (at least while empty of payload) principally by static lift, i.e. lift arising from buoyancy. In practice this implies that the vehicle must weigh less than the air it displaces; thus, its hull must be filled with a gas lighter than the ambient air, invariably helium in present-day applications.

A fully buoyant aircraft has the majority (though not necessarily all) of its weight supported by static lift even when fully loaded.   In essence, this is what is generally known as an airship. A small amount of dynamic lift is provided, typically by the lift generated by the craft's hull itself (sometimes with a contribution from varying the angle of engine thrust) to compensate for small changes in weight due to temperature variations, fuel consumption etc. The volume of gas changes with temperature as demonstrated by the Charles' and Boyle laws of gas expansion (*1*). Combined they give the general law of gases:

$$\frac{P_o V_o}{T_o} = \frac{PV}{T}$$

where P_o = pressure in initial condition, V_o is the volume in the initial condition and T_o is the temperature in the initial condition and P, V and T are the same variables in a new condition which may be a different temperature.

The aims of this paper are to present a review of recent developments in buoyant craft and based on research to date, select the most appropriate type of craft that might be used.

REVIEW OF RECENT DEVELOPMENTS IN TECHNOLOGY

The conventional classification of buoyant craft is by structural form. Non-rigid airships have their structure supported entirely by internal gas pressure and account for virtually all the craft in service today; however, there are serious negative scaling problems with constructing them in exceptionally large sizes. Semi-rigid airships consist of a pressure-supported hull with localised rigid stiffening elements (e.g. a keel). This type of structure is used in some current large airship projects, since it is cheaper and lighter than a full rigid structure but allows larger hull volumes than non-rigid. Finally, the traditional rigid structure was used in most of the well-known large airships of the period 1900-1939; it involves a complex load-bearing structure of rings and longitudinal members cross- braced and covered with non-load-bearing fabric, within which gas cells (also non-load-bearing) are contained. Although well suited to large sizes, the rigid structure is complex to construct and maintain; some suggestions have been made for its substitution by one where a hard outer shell bears the bulk of the load ('semi-monocoque'), but this introduces new problems (particularly with weight).

Despite these difficulties, a few projects based on the traditional rigid structure have been proposed in recent times.

Partially buoyant aircraft utilise static lift to support most of their empty weight, but dynamic lift for the payload (and a small proportion of the empty weight, such that the craft remains "heavy"- and thus more easily handled- while stationary and empty of load on the ground). Such craft are sometimes termed "hybrid airships". They can be divided (*2*) into two categories. 'Dynastats' use wing-generated lift, either through attaching wings to a gas-filled hull or by shaping the hull itself to generate lift (a lifting body). 'Rotastats'"have hulls with rotor blades, similar to those of helicopters, attached; the rotor blades are used to generate the dynamic lift, while forward propulsion may be via either the blades or separate propellers. Dynastats are short take-off and landing aircraft (STOL) and rotastats are vertical take-off and landing (VTOL) aircraft.

In structural terms, all the variants listed above are represented in the range of past and present hybrid designs. In the case of dynastats, the hull form is often radically different from that of the fully-buoyant airship, because of the aforementioned requirement to maximise the dynamic lift generated.

The idea of using airships for short-to-medium range scheduled passenger services gained some currency in the 1960s, partly in response to noise and other problems arising with then-existing passenger helicopter services. As with the latter, much initial interest tended to focus on airport feeder and inter-airport routes.

None of the more ambitious projects from this era came to fruition, although progress was made in enhancing and enlarging smaller craft. The mid-to-late 1990s saw a second revival of interest in buoyant aircraft. A wide variety of proposals were put forward and, although some again failed, others continue at the time of writing. It is, however, undeniable that much remains to be done, and that considerable uncertainty must continue to characterise any review of the future potential of this mode. Table 1 summarises some current or recent projects. It also outlines the notional craft design used for analysis in the field of passenger transport, the characteristics of which have been projected on the basis of a previous study (*3*). The Zeppelin N 07 is one of the first of the recent attempts to produce a modern airship, and is now in regular sightseeing service. It is likely to prove too small for scheduled transport, but outline plans exist for larger craft, up to 84 passenger seats.

The CargoLifter CL160 is a very large (larger than any other built to date) airship design optimised for the movement of heavy and outsize consignments, and partly funded by major German manufacturing firms. The aim is to have the first flight possibly taking place in 2004. A longer-term objective is the construction of an airship with a payload of 400-500t. Some possibilities are foreseen in unitised freight transport, but at present the company appears to be concentrating exclusively on the "heavy lift" market.

The ATG SkyCat series is a range of dynastats having a non-rigid structure and a form similar to two conventional airship hulls merged into a "flying wing". An air-cushion landing gear system allows operation from water or rough surfaces, and can provide suction to hold down the craft during ground operations. Present versions have 20t, 200t and 1,000t payloads. The prime markets are seen as being unitised freight transport (at varying ranges), for civilian users and strategic long-range military airlifting. Smaller craft are also seen as having applications in passenger transport and surveillance. A remotely-piloted prototype craft has been flown, and the first SkyCat 20 and SkyCat 200 are now under construction.

Performance

One notable characteristic of the buoyant aircraft is that it is a relatively slow mode by aviation standards. Typically, a fully-buoyant airship will cruise somewhere between 100 and 140km/h; the economic limit would appear to lie in the region of 160km/h, although faster airships have been projected from time to time. This is clearly considerably slower than the typical aircraft, although quite respectable in comparison with surface modes, particularly when account is taken of the buoyant aircraft's ability to use more direct routings than road or rail. It must be noted that a scheduled point-to-point speed must take account of the possibility of encountering headwinds, which are relatively more significant than for heavier-than-air vehicles owing to the lower cruising speed. Hillsdon (4) implies that, because of this, "the characteristics of an airship do not support scheduled passenger carriage …[except] in niche markets…".

In practice, airspeed can be increased above cruising speed to the maximum possible for short periods to mitigate wind effects, with the lower airspeed in the opposite direction compensating for additional fuel costs on a round-trip operation (5). Mowforth (6) suggests that 80% of cruise speed is an appropriate value to assume for average flight speed in passenger shuttle operations. This would imply a point-to-point average of 90-95km/h for typical present-day craft. Therefore, although the wind factor affects the possible average speed, it does not, on balance, do so sufficiently to rule passenger airships out entirely. However, the low average speed attainable suggests that fully-buoyant airships may be of questionable utility in scheduled passenger markets except where distances are short or airline competition weak.

Dynastats are characterised by a higher cruising speed than the pure airship, typically 200-300km/h. The factor of increase in cruising speed relative to the fully-buoyant airship is similar to that offered by high speed vessels relative to conventional ferries, but- as with ferries- there may be an operating cost penalty to be paid. Rotastats were mainly designed for short-range heavy lift operations, where speed was not generally considered critical. Hence, they did not tend to offer any significant speed advantage over the conventional airship.

In terms of individual vehicle size, the conventional airship offers significant economies of scale, principally due to the "square-cube law" whereby the surface area (and thus structure weight and air resistance) rises as the square of linear size but volume (and thus payload) rises as the cube. Material properties must theoretically impose a limiting size, but this would appear to be very large indeed, in excess of 500t payload and probably around 1,000t. Most proposals for modern freight-carrying airships have postulated a craft somewhere between 300t and 600t payload. The relevant factors for a dynastat-type hybrid are different, since the lift generated is partially dynamic (scaling as the square of size) and partially static (scaling as the cube). However, several dynastat proposals- the current ATG SkyCat being a relevant example- have envisaged payloads in the region of 500-1,000t. Furthermore, a dynastat can be built smaller than a fully-buoyant aircraft for a given payload, since only roughly half the volume of lifting gas is required. This is due to the payload plus part of the structure weight being dynamically supported; the total structure weight will generally be similar to or slightly in excess of that of the payload.

Operation of a conventional airship is subject to a number of problems which lessen the potential advantages of the mode.

- Equilibrium in flight:

A pure airship must remain in equilibrium (total disposable load + empty weight = lift) at all times. However, fuel consumption and temperature rises tend to "lighten" the craft, which must be compensated by reducing lift (i.e. releasing gas- uneconomic with helium) or ballast added (not generally practical during flight). A solution applied to the fuel weight problem in the past, and proposed for present-day designs such as the CargoLifter CL160, is the use of condensing equipment to recover water from the engine exhaust. The use of alternative fuels may also offer a solution. Vectored thrust (directing a component of engine thrust up or down) is also widely used to cope with small weight and buoyancy changes. Dynamic lift (using the airship's hull to generate lift in a similar manner to a wing) may also contribute (e.g. by lifting off "heavy" with dynamic assistance and lessening the dynamic lift as fuel is consumed).

- Ground handling:

The classical airship form is optimised for low air resistance in flight, but vulnerable to crosswinds on the ground, so that it must be allowed to swing with the wind while moored by the nose to some form of mast structure. This increases the amount of space required and complicates ground operations.

- Loading/unloading:

Again, the total weight of payload, ballast and fuel must remain constant at all times. This implies that either a new payload or an equivalent ballast weight, or possibly a combination, must be substituted for the freight being unloaded. The airship must be held in position during the operation, while remaining able to fly away in case of emergency. The difficulty of this process- particularly in the case of a heavy lift operation, where the payload will often be a single indivisible unit and the unloading site generally unprepared- cannot be underestimated. CargoLifter AG have adopted a solution developed for the Airfloat HL heavy lift airship design in the 1970s (*1*) with some modifications. The payload module is held in a loading frame, which is suspended, from a hoist on the airship (about which the craft can rotate with changing wind direction) and tethered to the ground by four cables. The frame also contains ballast and fuel tanks which can be filled as the payload is unloaded.

- Low-speed control:

Take-off and landing are carried out at low or zero forward speed, when conventional control surfaces are ineffective, so that an alternative means of inducing control forces must be found. Traditionally this involved large (and now uneconomic) ground crews; modern approaches generally make use of control thrusters on the airship and automated mooring systems.

Costs

The principal problem in attempting to assess the financial and economic performance of the airship is the general dearth of real-world experience relating to the mode. Nevertheless, a considerable amount of research has been directed towards the quantification of the airship's operating economics, particularly with regard to freight transport. Table 2 indicates some past estimates of freight airship operating costs, brought to common price and currency values. The payload, operating speed and range of the airship are given in each case, since these are significant determinants of operating cost. The table bears this out; operating costs decrease with size and increase with speed. The results presented by Nayler and Howe would suggest that as speed increases costs decrease per t-km. The high values quoted by Howe (*7*) do not have an obvious explanation. It is likely that a combination of the long range (i.e. more fuel

weight at the expense of payload) projected and the arbitrary assumptions made regarding the relationship between direct and indirect costs (which result in a higher indirect cost level than Coughlin's (*8*) more fully developed figures) account for the majority of this. Otherwise, there is a remarkable degree of agreement between sources within the same size and speed range.   The economics of passenger-carrying airships, particularly in scheduled point-to-point service, are a less well-researched area.

From the literature available, a hybrid (dynastat) solution for passenger transport seems the most appropriate, in terms of it being a more effective competitor to airlines than the (slow, unreliable and potentially difficult to handle) pure airship. Detailed technical and economic models for a hybrid passenger-carrying design (originally intended for short-range city-to-airport flights, and never realised) were available in Goodyear Aerospace Corporation (*3*). Since the design proposed would utilise a tiltrotor-type system for propulsion and for dynamic lift at low or zero forward speed, it was considered that the propulsion system could be assumed to be based on that of the notional CTR2000 tiltrotor aircraft design (*8*).

The parametric models used in the Goodyear study were applied in order to develop a notional airship design around the CTR2000 propulsion systems, then project its capital and operating costs. As an initial step, it was assumed that the resulting vehicle would have a capacity of 200 passengers. The weights of the various components were then calculated by applying appropriate expansion factors (e.g. hull weight proportional to payload to the power of two-thirds, since volume is directly proportional to payload and weight directly proportional to surface area) to the Goodyear weight data.

Allowing for the dynamic lift from the rotors, the necessary buoyant lift to support the craft's total weight was then calculated. This allowed a new value to be derived for hull weight, and the process was iterated to convergence. Cruising power was assumed to be in the same proportion to maximum power as in the original Goodyear study. Once cruising power and volume were known, the cruising speed was derived by assuming that the non-dimensional performance coefficient of the design remained constant at the increased size. This gave a cruising speed of 114 knots (211km/h).

SUMMARY

The paper reviews the current technology available and under development in buoyant aircraft and examines performance and costs in terms of their potential for more widespread use.   From the available literature the authors suggest a craft CTR2000 tiltrotor aircraft in terms of likely potential for the passenger transport market using the information supplied by the various studies covered but a full detailed analysis. As the technology is not in common use and much of it is at prototype stage, estimating costs etc is difficult and is likely to be fraught with oversimplification of assumptions in relation to markets, demand etc.

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TABLE 1 Selected Current Buoyant Aircraft Projects

Manufacturer	Zeppelin	CargoLifter	ATG	ATG	ATG	n/a
Model	N 07	CL160	SkyCat 20	SkyCat 200	SkyCat 1000	Notional passenger dynastat design
Structure	Semi-rigid	Semi-rigid	Non-rigid	Non-rigid	Non-rigid	Rigid and non-rigid options possible
Buoyancy	Full	Full	Partial	Partial	Partial	Partial
Helium volume (m^3)	8,225	550,000	32,000	457,500	2,000,000	40,000
Length overall (m)	75	260	81	185	307	108
Cruise speed (km/h)	115c	100	130	139	185	211
Max speed (km/h)	130	140	148	167	204	Not calculated
Range (km)	Not known	10,000	2,266	5,966	7,400	800
Max payload (t)	1.9	160	20	200	1,000	20
Passenger seats	12	n/a	c.100	c.1,000	n/a	198
Engines	3×149kW petrol	4×1,425kW diesel, plus thrusters	4×450kW diesel	4×6,000kW gas turbine	6×11,250 kW gas turbine	4×5,445kW gas turbine
First flight	1997	2004	2003 possibly	2005 possibly	2007 possibly	n/a
Service entry	In service	Post-2005	Not clear yet	Not clear yet	Not clear yet	n/a
Capital cost (€ million / $ million)	6.8 / 6.66	51 / 50	Not clear yet	Not clear yet	170 / 166	35 / 34

Sources: Jackson (1998) (*10*), Nayler (1998) (*11*), ATG (2000) (*12*) , ATG website (http://www.airship.com)

TABLE 2 Freight Airship Operating Cost Estimates

Source	Payload (t)	Operating speed (km/h)	Range (km)	Cost (€/t-km/$/t-km), mid-1999
Howe (1971) (*7*)	300	191	8000	0.49 / 0.48
Howe (1971) (*7*)	300	171	8,000	0.53 / 0.52
Howe (1971) (*7*)	316	166	8,000	0.47 / 0.46
Coughlin (1973) (*8*)	319	186	1,600	0.16 / 0.15
Ausrotas (1974) (*13*)	60	160	3,200	0.25 / 0.24
Madden/ Bloetscher (1974) (*14*)	101	160	2,400	0.17 / 0.16
Smith/Ardema (1974) (*15*)	156	185	5,000	0.13 / 0.12
Nayler (1979) (*16*)	400	145	2,000	0.09 / 0.08
Nayler (1979) (*16*)	100	140	1,000	0.17 / 0.16
Nayler (1979) (*16*)	100	145	1,000	0.15 / 0.14
Nayler (1979) (*16*)	30	145	600	0.29 / 0.28
Nayler (1979) (*16*)	7	140	400	0.56 / 0.55
Nayler (1981) (*17*)	75	139	1,850	0.20 / 0.19
CargoLifter AG (1997) (*18)*	160	100	10,000	0.15 / 0.14