TRANSPORT EFFICIENCY OF CONVENTIONAL AIRSHIPS AND HYBRID AIRSHIPS IN COMPARISON

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Abstract

Lately, there is renewed momentum in in the aviation sector in using airships for transport purposes, driven by the emerging of hybrid airships, which generate significant lift with their uniquely-shaped hull. The main claimed advantages of hybrids are a reduction in overall vehicle size and improved ground handling. The presented study shall complete these qualitative points with a comparison of the transport efficiency of both airship types and their suitability for use in dedicated airship markets.

Keywords

Aerospace, Airship, LTA, Hybrid Airship, Lifting Body, Preliminary Design, Zeppelin, Luftschiff, Hybridluftschiff

1. INTRODUCTION

The aim of this study is to present a comparison of the transport efficiency of conventional and hybrid airships. For an apples-to-apples comparison, the vehicles have to be as similar as possible in terms of mission performance, as in reality they would compete for the same markets. Ideally, reference missions would have to be derived from those markets, and vehicles of both types would have to be designed to serve those missions and sized to give optimum performance. Yet, this would also limit the comparison to those specific mission, let alone the fact that there are hardly any reference missions/markets which would be typically served by airships. Instead, a simplified approach is used, where the vehicles are designed to provide the same maximum useful load.

In terms of efficiency, several performance aspects are compared, ranging from aerodynamic/fuel efficiency over mission-related performance to cost. The comparisons include vehicles sized for two different useful load categories, 2t and 20t respectively, to demonstrate the influence of vehicle size where relevant.

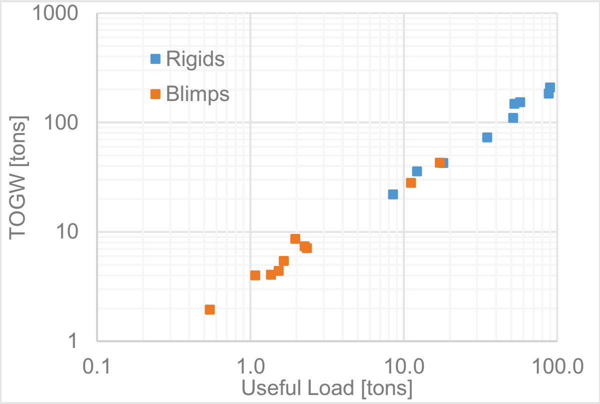
The study is concluded by presenting several legacy, current and potential future airship missions. Based on the previous findings, the suitability of both airship types to serve those missions is judged.

2. VEHICLE SIZE AND DIMENSION – CONVENTIONAL AIRSHIP

In operations, payload and fuel can be traded one for the other to comply with different missions, but their overall sum will have to remain constant. Introducing:

$$m_{UsefulLoad} = Payload + Fuel$$

The volume and the gross weight of a conventional airship are closely related. The relation between airship empty weight and TOGW (total weight) can be derived from statistics. Defining the useful load as the Total Lift minus the empty weight, the statistic can be altered to give a direct relation between useful load and the lift required to carry it:



With the TOGW determined from the useful load, the envelope volume is calculated, taking into account the air density differential at ballonet ceiling σ, the helium purity and the heaviness ratio – or its inverse, the buoyancy ratio BR:

$$Vol_B = \frac{BR_B TOGW_B}{1.056\frac{kg}{m^3}(2-\sigma^{-1})f_{purity}}$$

With the unit lift of helium in air 1.056kg/m³

And $(2\text{-}\sigma^{-1})$ as a conservative approach to account for the ballonet volume from [1]

Assuming the airship shape to be an ellipsoid (prolate spheroid), the diameter and length are calculated from the volume based on the fineness ratio FR of the airship:

$$FR_B = \frac{L_B}{Dia_B}$$

$$Dia_B = \left(\frac{6Vol_B}{\pi FR_B}\right)^{\frac{1}{3}}$$

The span of the horizontal tail needs to be determined for estimating the lift efficiency of the vehicles. Therefore, a simple tail sizing based on tail volume coefficients is employed to find the tail fin area and, subsequently, the tail span:

$$S_{HT\_B} = \frac{C_{HT} L_B Vol_B^{\frac{2}{3}}}{L_{HT}}$$

$$b_{HT\_B} = 2\frac{Dia_B}{L_B}\sqrt{\left(\frac{L_B}{2}\right)^2 - {L_{HT}}^2} + 2\sqrt{\frac{S_{HT\_B}}{2} AR_{HT}}$$

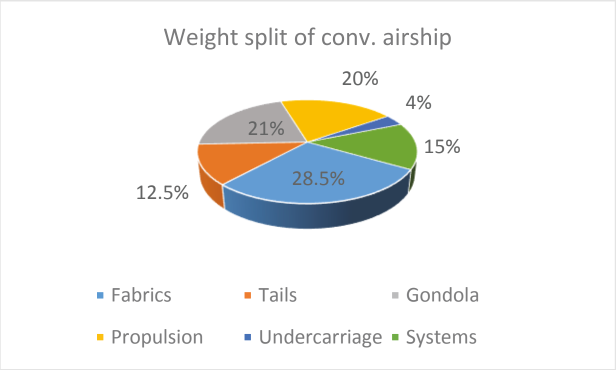
With the tail aspect ratio $AR_{HT} = 0.5$ as typical value for narrow airship fins,
The tail volume coefficient $C_{HT} = 0.065$,
And the tail lever arm $L_{HT} = 0.35$, as proposed in [1].

3. VEHICLE SIZE AND DIMENSION – HYBRID AIRSHIP

The TOGW drives the required total lift and hence vehicle size. To find the TOGW, an empty weight estimate of the airship is required, as TOGW is the sum of useful load and empty weight.

3.1. Empty weight split

As no statistics for the weight of hybrid airships exist, their weight is derived from the empty weight of conventional airships. Empty weight split for a conventional airship as given in [1]:



When sized for the same speed and payload, the propulsion system, fuel system and the cabin incl. payload accommodation can be assumed to be equal in weight for both airship types. Same shall be assumed for the system weights and for the undercarriage, all in total 59% of the weight are the same.

3.2. Fabric weight

3.2.1. Surface area

Due to the smaller airship volume, the envelope surface area of a hybrid airship is smaller, though a multi-lobed hybrid airship contour requires more envelope material than an ellipsoid of the same volume and with the same length, width and height. For a three-lobed configuration, the surface area according to [1] is:

$$O_{Hyb} = 1.081 O_e$$

$$O_e = 4\pi\left[\frac{\left(\frac{L_{Hyb}}{2}\right)^p\left(\frac{B_{Hyb}}{2}\right)^p + \left(\frac{L_{Hyb}}{2}\right)^p\left(\frac{H_{Hyb}}{2}\right)^p + \left(\frac{H_{Hyb}}{2}\right)^p\left(\frac{B_{Hyb}}{2}\right)^p}{3}\right]^{\frac{1}{p}}$$

Where p=1.6075

In addition to the outer surface hull, a multi-lobed body requires “walls” that connect the upper and lower part of the airship surface at each point where two lobes intersect. The total area of two such walls can be approximated by an elliptical intersection face:

$$A_{Hyb} = \pi 0.9 L_B \sqrt{\left(\frac{Dia_{L\_Hyb}}{2}\right)^2 - \left(\frac{Dia_{L\_Hyb}}{4}\right)^2}$$

Adding the weight of the internal wall fabric to the outer hull fabric, the total fabric area of a 3-lobed hybrid airship is nearly the same as that of a conventional airship with the same total lift. The wall material has to be as strong as the outer hull. Some weight reduction is possible since the internal walls won’t require a protection layer for UV radiation and other environmental deterioration. Assuming a 30% weight reduction for the internal wall fabric, the total envelope fabric weight of a hybrid airship is approximately 10% lighter than on a conventional airship with the same total lift. Hence, the weight saving due to less fabric is:

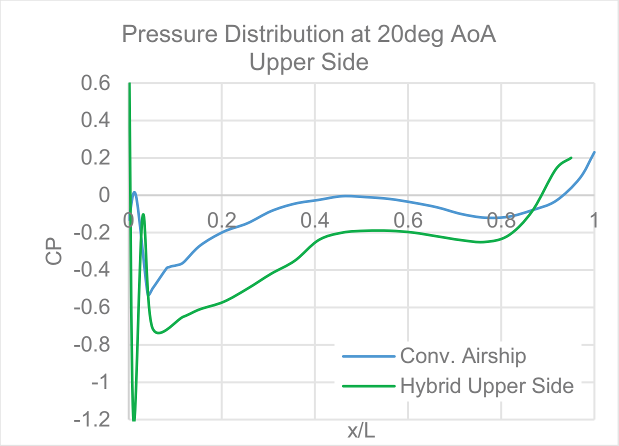
$$f_{FabricArea} = \frac{O_{Hyb} + 0.7A_{Hyb}}{O_B} \cong 0.90$$

3.2.2. Loads on hull

The hull load is driven by the internal overpressure (the pressure differential between the outside air pressure and the internal pressure), which in turns is a function of the aerodynamic stagnation pressure acting on the airship, so essentially a function of airship speed. When designing both airships for the same maximum speed, the dynamic pressure q and hence the internal pressure can be the same. The relation between internal pressure and fabric load is:

$$\sigma_{hoop} = \frac{\Delta p_{intern} Dia}{2 t_{skin}}$$

As the hybrid airship features smaller lobe diameters, the skin thickness could be reduced by the diameter ratio, leading to a weight decrease of approx. 35% versus a blimp, disregarding the effects of external pressure distributions. However, pressure loads along the body of a hybrid airship are higher than on conventional airships, due to the increased aerodynamic lift being generated by higher suction pressure. A qualitative comparison is obtained by plotting hybrid airship CP data from [3] together with conventional airship CPs from [4]:



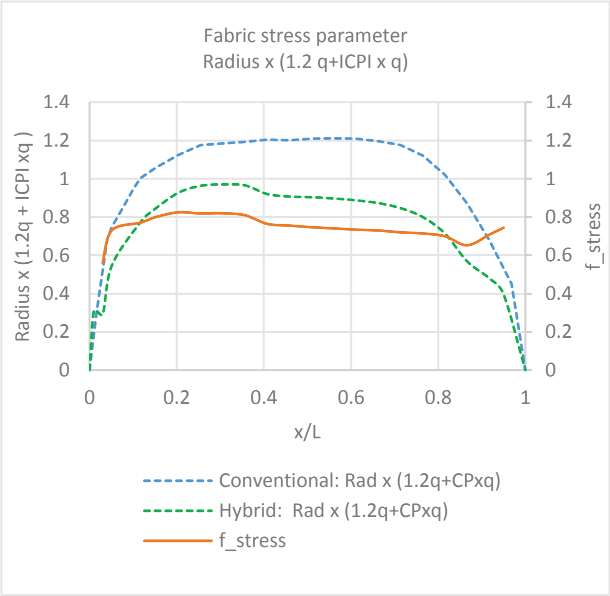
The largest hoop stress difference will occur where the product of delta pressure and body radius has its peak. Defining the fabric stress parameter:

$$f_{stress} \sim \frac{R_{Hyb}}{R_{Conv}} \frac{\Delta p_{Hyb}}{\Delta p_{Conv}} = \frac{R_{Hyb}}{R_{Conv}} \frac{p_{Hyb_{intern}} + \Delta p_{Hyb_{extern}}}{p_{Conv_{intern}} + \Delta p_{Conv_{extern}}}$$

$$= \frac{R_{Hyb}}{R_{Conv}} q \frac{1.2 + |cp_{Hyb}|}{1.2 + |cp_{Conv}|}$$

With the internal pressure being 20% larger than the maximum dynamic pressure q, typically.

For a three-lobed hybrid airship, that requires only 65% the lobe diameter of a conventional airship for the same total lift, the fabric stress parameter along the body length is estimated from the above data as:



From the above graph:

$$f_{FabricStress} = \max\left(\frac{R_{Hyb}}{R_{Conv}} \frac{1.2 + |cp_{Hyb}|}{1.2 + |cp_{Conv}|}\right) \cong 0.80$$

Skin thickness for the hybrid airship could be reduced to approx. 80%. It shall be noted though, that the minimum skin thickness for airship fabrics is limited by manufacturing and handling constraints. Further, reducing skin thickness also increases the helium leak rate of a fabric, so the actual weight saving might be smaller than 20%.

3.3. Tail sizing and derivation of fin weight

Similar to the sizing of the conventional airship fins, tail volume coefficients are used to find the hybrid airship tail size:

$$S_{HT\_Hyb} = \frac{C_{HT\_Hyb} L_{Hyb} Vol_{Hyb}^{\frac{2}{3}}}{L_{HT\_Hyb}}$$

As the hybrid airship provides the opportunity of larger variations in payload mass, the trim capability of the tail fins will have to be larger than for a conventional airship. Thus, the tail volume coefficient is chosen 20% larger, whereas the tail lever arm is set to 38% half body length, as proposed in [1].

The resulting tail fin area is nevertheless smaller for a hybrid airship than for a conventional airship with the same total lift, mainly due to the overall smaller vehicle size (volume). Accordingly, the fin weight factor is:

$$f_{FinArea} = \frac{S_{HT\_Hyb}}{S_{HT\_B}} \cong 0.80$$

3.4. Empty weight estimaiton

With the assumptions stated above, roughly 59% of the empty weight are the same for a hybrid and a conventional airship (propulsion, systems, cabin). Fabric and fin weights can be scaled down with the presented factors:

$$\begin{aligned} OEW_{Hyb} = OEW_B 0.59 &\\ &+ f_{FabricArea} f_{FabricStress} m_{fabric\_B} \\ &+ f_{FinArea} m_{fins\_B} \end{aligned}$$

$$\begin{aligned} OEW_{Hyb} &= OEW_B 0.59 + 0.9 \cdot 0.8 \cdot 0.285\, OEW_B \\ &+ 0.8 \cdot 0.125\, OEW_B \end{aligned}$$

$$OEW_{Hyb} = OEW_B\, 0.90$$

And consequently:

$$TOGW_{Hyb} = OEW_B\, 0.90 + m_{UseLoad}$$

3.5. Hybrid airship dimensions

With the TOGW determined above, the volume is found as:

$$Vol_B = \frac{BR_{Hyb} TOGW_{Hyb}}{1.056 \frac{kg}{m^3} (2 - \sigma^{-1}) f_{purity}}$$

The derivation of the hybrid airship dimensions follows the procedure sketched in [1] for a three-lobed airship. Diameter of an Ellipsoid with the same Volume and FR:

$$Dia_{Hyb\_eqv} = \left(\frac{6Vol_{Hyb}}{\pi FR_{Hyb}}\right)^{\frac{1}{3}}$$

Max. Lobe diameter of three-lobed body, airship length, height and width (without fins):

$$Dia_{L\_Hyb} = 1.5\ Dia_{Hyb\_eqv}$$

$$L_{Hyb} = FR_{Hyb}\ Dia_{Hyb\_eqv}$$

$$H_{Hyb} = Dia_{L\_Hyb}$$

$$W_{Hyb} = 2\ Dia_{L\_Hyb}$$

Span of the airship incl. tail fins:

$$b_{HT\_Hyb} = 2\frac{Dia_{L\_Hyb}}{L_{Hyb}}\sqrt{\left(\frac{L_{Hyb}}{2}\right)^2 - L_{HT}{}^2} + 2\sqrt{\frac{S_{HT\_Hyb}}{2}AR_{HT}}$$

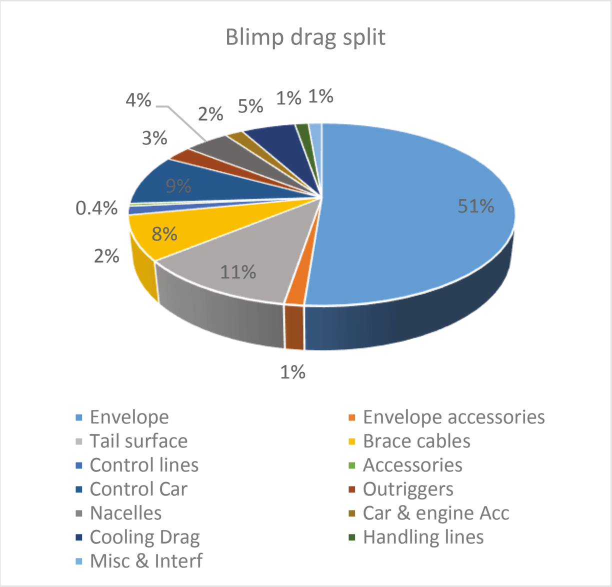
4. AERODYNAMIC DRAG

Quadratic drag polars are estimated for both airship types. Vehicle drag is split into two main components:

$$Drag_{Total} = Drag_{Zero\_Lift} + Drag_{Lift\_Depdendent}$$

4.1. Zero-Lift Drag

It is convenient to handle the zero-lift drag in the “drag area” from, that is, drag force divided by dynamic pressure q, or drag coefficient multiplied by reference area. In this form, component drag figures can be added from different sources without taking into account differences in reference area. Similar to the weight estimation, it is also assumed for aerodynamics that both vehicles have the same cabin and propulsion system/nacelles. Main difference is the drag of the hull, the tail fins and the lift-depdendent drag. Typical drag split of a non-rigid, conventional airship [2]:



Drag area formulation, as used for envelope and tails:

$$cdS = S_{wett}\ cf\ FF$$

With the friction factor cf as presented in [5]:

$$cf = \frac{a}{\log(Re)^b}$$

Form factor to account for the pressure drag of the envelope as from [5]:

$$FF_{env} = 1 + c\left(\frac{1.5}{FR^{1.5}} + \frac{7}{FR^3}\right)$$

Coefficients are given as a = 0.455, b = 2.58 and c = 1.0 in [5], but have been re-calibrated to better fit airship data from WT tests and flight testing.

Form factors to account for pressure drag and sweep on the tail fins, for typical airship fin geometries:

$$FF_{tc} = 1.206$$
$$FF_{\varphi} = 0.983$$

Analyzing data from [2], the drag area of cabin and propulsion system is about as high as 40% of the airship envelope drag. The drag figure is calculated once for the conventional airship and then also used for the hybrid airship. Similarly, according to [2], the drag of the other airship components sum up to 25% of the envelope drag figure. This “misc” drag is calculated separately for the conventional and the hybrid airship, so it is assumed that the hybrid airship features a smaller misc drag due to overall reduced vehicle size.

$$cdS_{Cabin+PPS\_Blimp} = 0.40\ cdS_{Env\_Blimp}$$
$$= cdS_{Cabin+PPS\_Hybrid}$$

$$cdS_{Rest} = 0.25\ cdS_{Env}$$

Through its dependency on the Reynolds number, the zero lift drag components as presented above change with speed and altitude. This is also reflected in the following chapters and helps to understand the performance of the airship types.

4.2. Lift-Dependent Drag

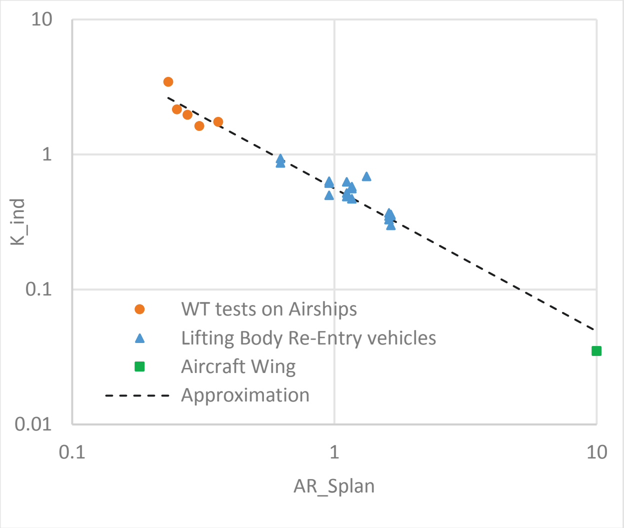
Both airship types generate additional drag from aerodynamic lift. The generalized expression is:

$$CDi = K_{ind}\ CL^2$$

The factor K_{ind} depends on the vehicle aspect ratio and the lift efficiency factor k, which denotes the efficiency of the body to generate lift, referenced to an elliptical lift distribution which has k=1.0 per definition:

$$CDi = \frac{CL^2}{\pi\ AR}k$$

Bodies with low aspect ratio, lifting bodies without pronounced wings and also airships usually feature k-factors significantly higher than 1.0. The dependency of K_{ind} on 1/AR can be assumed linear for aircraft wings. When treating low-AR vehicles, the dependency on AR has to be slightly adapted to fit available data, see also [1]. The following graph includes airship wind tunnel data from [7] and [8], flight test data of lifting bodies [6], as well as values achievable with aircraft wings:



The above graph assumes that aspect ratio is calculated from the vehicle planform area. Consequently, drag coefficients CD and lift coefficients CL are also referenced to the planform area Splan, instead of the airship-common referencing to Vol$^{(2/3)}$:

$$AR_S = \frac{b^2}{Splan}$$

Conventional airships and three-lobed hybrid airships [1]:

$$Splan_B = 2\,Vol_B^{\frac{2}{3}}$$

$$Splan_{Hyb} = 2.4\,Vol_{Hyb}^{\frac{2}{3}}$$

Note that the span b is the larger value of the airship max. diameter and the tail span from fin tip to fin tip (cross-tail arrangement assumed).

5. PRESENTATION OF KEY VEHICLE DATA

To compare conventional with hybrid airships, vehicles of either type were designed according to the methodology presented above. To study the effect of vehicle size, separate designs with 2t useful load and 20t useful load are treated. Buoyancy ratio for the conventional airships is 94%, similar to the Zeppelin NT, while for hybrid airships the selected value of 60% hints to lately-developed hybrid airships. Ballonet ceiling is set to 6000ft for all designs. All hybrids feature three-lobed bodies.

	2t Useful Load	
	Blimp	Hybrid
TOGW	6'393kg	5'933kg
Volume	7'363m³	4'361m³
Empty Weight	4'393kg	3'933kg
FR	4.0	3.0
BR	94%	60%
Length	60.82m	42.16m
Max. Diameter	15.2m	9.37m
Total Span	19.24m	20.78m

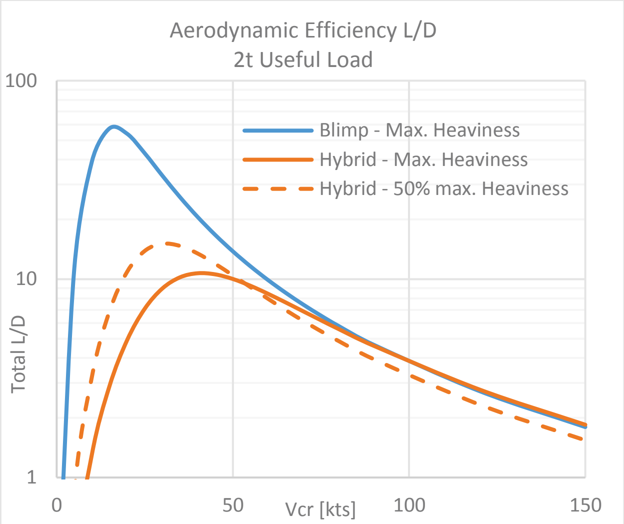
	20t Useful Load	
	Blimp	Hybrid
TOGW	51.0t	47.8t
Volume	58'780m³	35'130m³
Empty Weight	31.0t	27.8t
FR	4.0	3.0
BR	94%	60%
Length	121.6m	84.5m
Max. Diameter	30.4m	18.78m
Total Span	38.5m	41.67m

6. AIRFRAME AERODYNAMIC EFFICIENCY

The aerodynamic efficiency relates the lift generated by the vehicle to its aerodynamic drag. For airships, the (static) buoyant lift adds to the aerodynamic lift, hence:

$$L/D = \frac{L_{buoyant} + L_{aero}}{D}$$

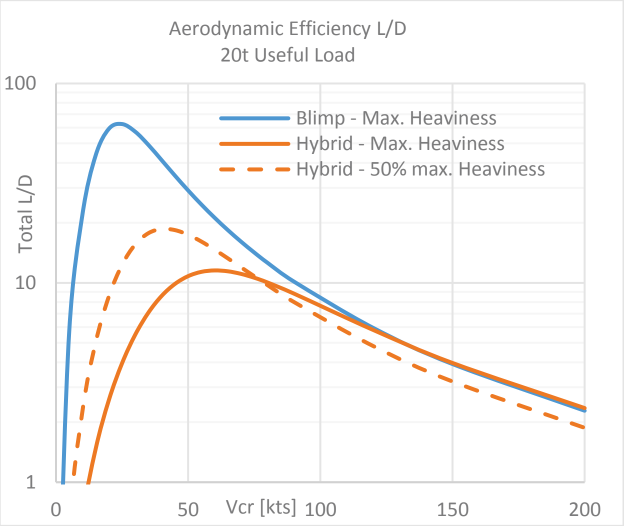
Hybrid airships achieve a higher aerodynamic lift-to-drag ratio, as their body is more suitable for generating aerodynamic lift. Yet, their total L/D is lower than for conventional airships, as it is less drag-efficient to generate aerodynamic lift than to have buoyant lift. This result is illustrated in the following graph:



The hybrid airship L/D at max. heaviness is just above 10, whereas the conventional airship L/D exceeds this figure drastically. Note that the hybrid airship comes closer to the classic airship L/D the lighter it gets. This already hints at an advantage of hybrid airships: They allow for more operational flexibility. Note also that the best L/D of hybrid airships is at higher speeds, which is a direct result of the lift-induced drag. It is more drag-efficient to generate aerodynamic lift by speed than by angle of attack or higher lift coefficient.

There is actually one more fundamental relation hidden in the L/D comparison, which relates to the optimal size of hybrid airships, when comparing to conventional airships.

Note that in the above picture, the break-even point in L/D for both airships is at roughly 90kts for vehicles with max. 2t useful load. Drawing the same figure for airships with 20t useful load, the break-even speed rises to approx. 135kts:



Size seems to favor conventional airships. This is a result of the so-called square-cube-law, which relates the scaling rules of volumes to that of areas/surfaces. When a body is scaled linear with its dimensions, its volume will grow by the power of three, while its (surface) area only grows by the power of two. One result of this "law" is the anticipated size trend of conventional tube-and-wing aircraft. Their weight is believed to be proportional to the volume, whereas their aerodynamic lift is proportional to the (wing) area. So by that rule, large aircraft would require an over-proportionally larger wing than small aircraft. (A more detailed investigation in [9] suggests a weight-scaling to the power of 2.1 rather than 3, which is still higher than the lift-scaling to the power of two).

For airships, the consequence of the square-cube-law has an opposite effect. Here, (buoyant) lift scales with the volume, so it grows with the power of three of dimensions. Weight mainly scales with envelope area, which grows only quadratic with dimensions. The TOGW graph on page 1 hints that by its tendency the law holds true in reality, although the difference between weight scaling and lift scaling is much weaker than the theory suggests, which is in line with the findings on aircraft.

In essence, the square cube law dictates, that buoyant vehicles tend to benefit from increasing dimensions, while aerodynamic vehicles are rather penalized. The L/D curves presented for conventional and hybrid airships highlight this relation. Hence the larger the vehicles get, the larger the gap in aerodynamic efficiency for both vehicles will become.

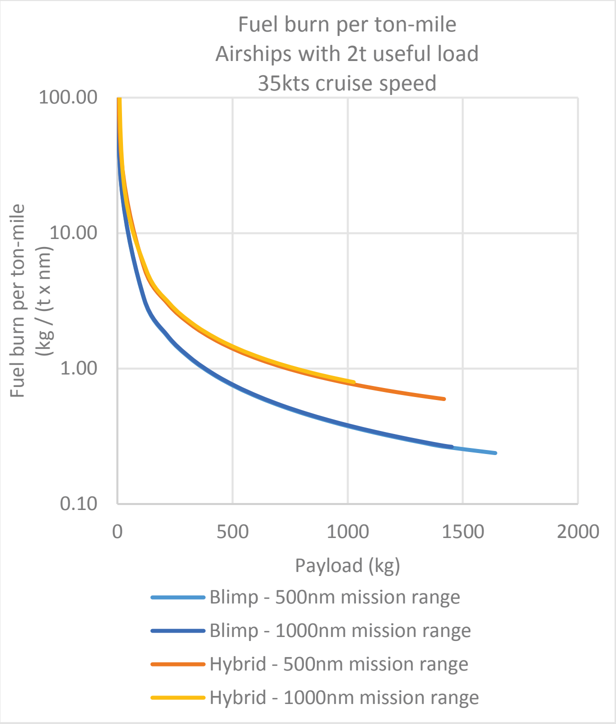
7. FUEL EFFICIENCY

With the definition of the range factor RF for propeller-driven aircraft, total L/D is a direct measure of the fuel required to fly a certain range:

$$\text{RF}=\frac{\text{L/D}\ \eta_{propeller}}{cPA}\ \frac{1}{m}$$

Fuel efficiency depends mainly on the aerodynamic efficiency of the airframe. As shown in the previous chapter, buoyant vehicles achieve a higher aerodynamic efficiency than hybrid airships (and aircraft). Hence, conventional airships are always more fuel-efficient than hybrid airships.

Although conventional airships have to carry ballast when flying at small payloads, their fuel burn per payload is still superior to hybrid airships, as shown in the following graph.



8. OPERATIONAL PERFORMANCE

Although being designed to provide the same useful lift, both airship types show differences in operational performance. First, the payload-range diagram shall compare the operational flexibility in terms of range, payload and speed. Second, the payload-endurance diagrams will show the applicability of both types for missions where time on station is more relevant.

8.1. Payload-range

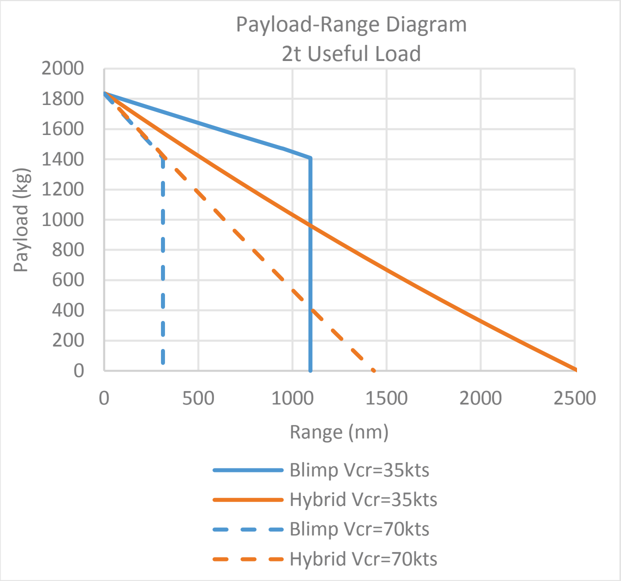
Both airships will have their optimum range at the speed of max. L/D. For conventional airships, the cruise speed was set to a minimum of 35kts, which is a figure from practical experience to be able to counter headwinds and also limit crew duty times on long range flights. Breguet range equation:

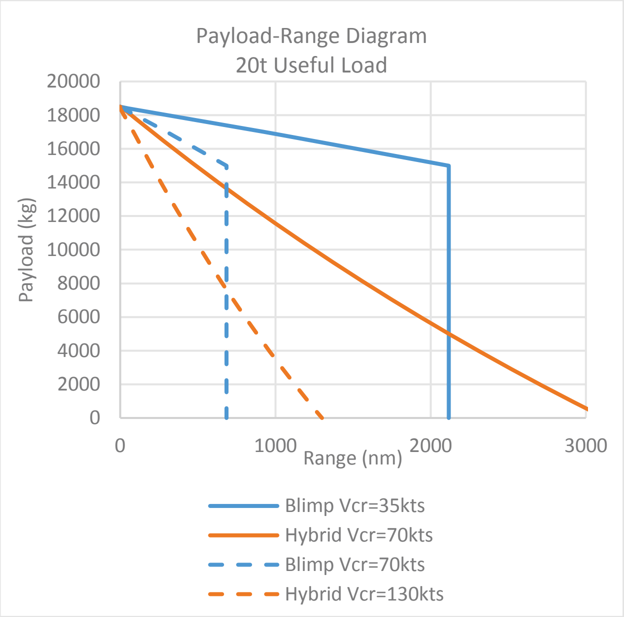
$$\text{Range}=\frac{L/D_{total}\ \eta_{propeller}}{cPA}\ ln\frac{m_A}{m_E}$$

m_A	weight at begin of range flight, set to 99% TOGW to account for the fuel burn during T/O and climb
m_E	weight at end of range flight. Includes fuel reserves (100kg for 2t vehicles, 1t for 20t)

c_{PA} = 230g/kWh (Aviation Diesel), $\eta_{Propeller}$ = 75%

m_E is the mass with all usable fuel burnt. To counter the weight loss from burning fuel, airships would take off statically heavy. The maximum fuel burned on the full mission must not be higher than the difference between the airship maximum heaviness and its minimum heaviness. Consequently, mission range is limited by the allowed heaviness range. Also, conventional airships will have to take ballast, when payloads are small, to keep the heaviness at landing within the allowed limits, which increases the relative fuel burn per payload. The described effects of minimum static heaviness vanish for hybrid airship concepts, provided the design buoyancy ratio is chosen low enough.



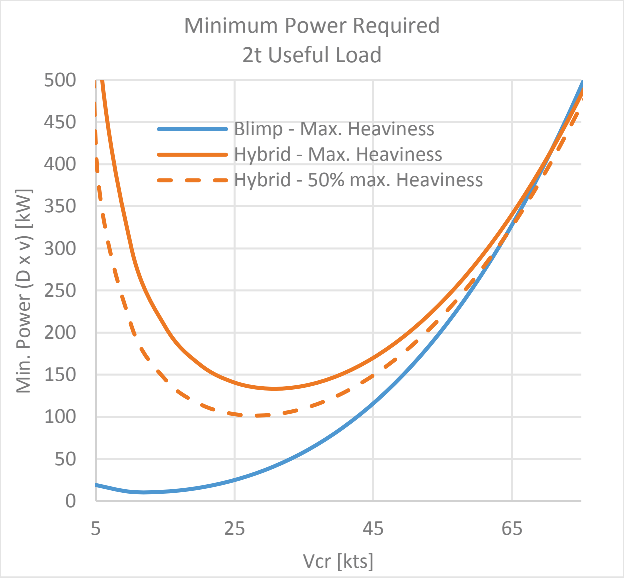


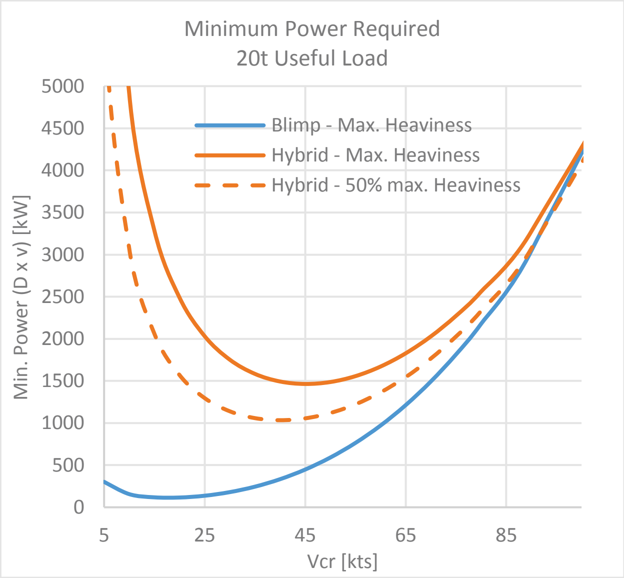
Note that the starting point is lower than the useful load to which the airships were designed due to fuel reserves and T/O & climb fuel provisions. Due to its better aerodynamic efficiency, the conventional airships offer higher payloads at short ranges. Yet, due to the small heaviness range, the maximum range is just about half of the hybrid airship range.

Another noticeable fact is the influence of increased speed. The conventional airships loose more than half of their range, when speed is increased (doubled, in the shown cases). Here the explanation lies in the use of dynamic lift. For conventional airships, speed is only a disadvantage due to the increase of drag (quadratic with speed). For hybrid airships, there is on the one hand the disadvantage of the zero-lift drag increase with speed. On the other hand, speed helps to generate the required dynamic lift at reduced CL, thus decreasing lift-dependent drag.

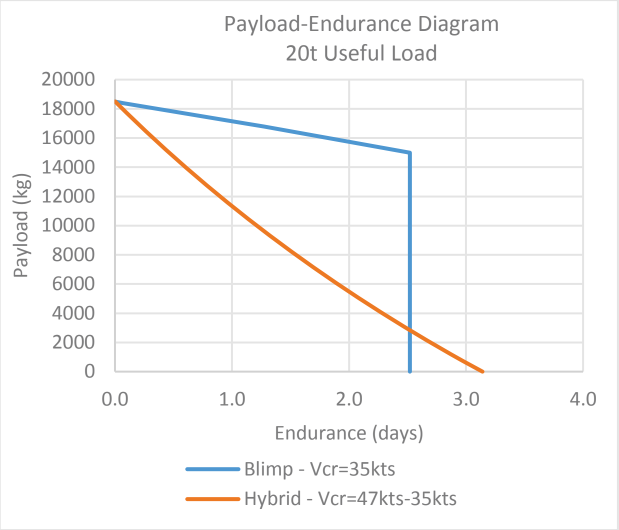
8.2. Payload-Endurance

Best endurance is achieved when flying at the speed of minimum required power. Here, clear advantage is on conventional airships, since the majority of the lift comes from buoyancy and is thus provided without consuming any power. The minimum power consumption of the hybrids depends on their inflight weight. At the end of a long mission, minimum power levels can approach the figures of conventional airships. Consequently, they will reduce speed or climb when burning fuel.





To draw payload-endurance diagrams, a practical minimum speed for loitering is defined to enable station-keeping also in headwinds. Figures around 20kts should be enough as no downrange is required when loitering. This would however result in throttling the engines back to very low power levels. When operating close to idle power, relative fuel consumption of combustion motors will rise again, so even when assuming one engine switched off for loiter, the endurance figures calculated with a close-to-minimum specific fuel consumption would be too high. Hence the minimum speed is set to 35kts again, which is more penalizing for the conventional airships.

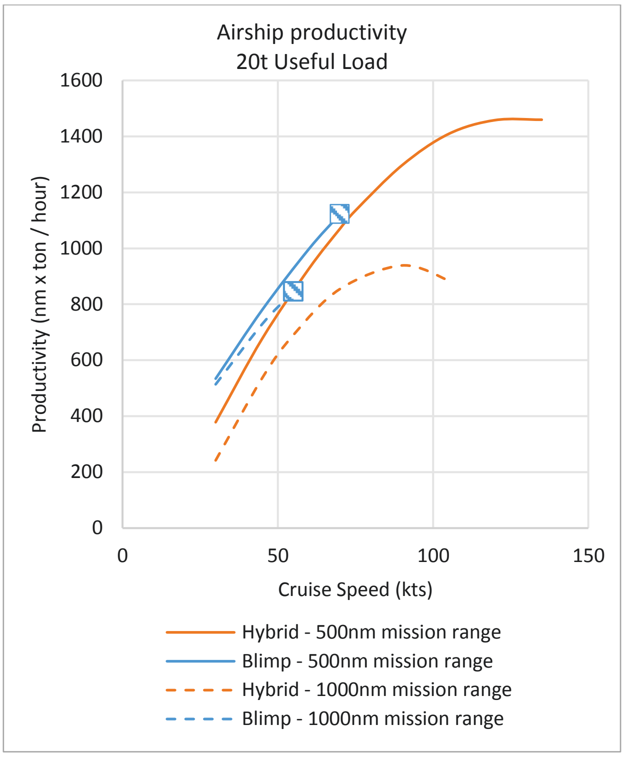


For long endurance flights, the advantage of lower minimum required power of conventional airships clearly over-compensates their limitation in absolute fuel burn due to limited static heaviness range.

9. TRANSPORT EFFICIENCY

For transport networks, speed does play a role. A parameter to reflect this is the productivity in ton-miles per day, or per hour as shown in the graph below.

In terms of productivity, hybrid airships can play their advantage of trading payload for fuel. Conventional airships are limited in terms of total mission fuel due to heaviness range limitations, which ultimately also limits their maximum cruise speed over a given mission range. On hybrids with low buoyancy ratio, these limitations are virtually non-existent, so they can go faster for the cost of increased fuel burn. That raises productivity of hybrids above those of conventional airships. Yet the graph also shows that on longer missions, the higher fuel consumption of hybrid airships due to worse aerodynamic efficiency eats into the available payload, so the productivity advantage goes down with increasing sector length. Note that going faster also requires more powerful (and thus heavier) engines, which is not reflected in the following graph.



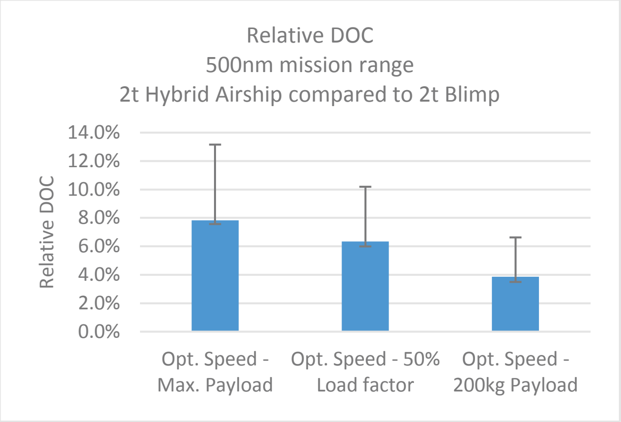
10. COST EFFICIENCY

One general advantage of hybrid airships is the reduced overall size. In the measures presented so far, vehicle size is only indirectly treated via reduced weight and reduced friction drag. Size however is a key parameter when it comes to vehicle cost, namely acquisition cost/capital cost and accompanying cost like insurance or maintenance.

To study the effect of size-related vehicle cost of hybrids versus conventional airships, a simplified direct operating cost DOC model was set up, compromising the cost factors:

- Depreciation/Capital
- Crew
- Fuel (incl. oil)
- Insurance
- Maintenance
- Helium

The relative cost shares of the cost model were compared to available airship cost breakdowns. As is usual with cost, data availability is bad and deviations between different cost splits are significant. Error bars in the relative cost diagrams indicate the maximum and minimum deviations from the simplified cost model, when comparing to data from [10], [11], [12].



At full payload, the conventional airship would provide a slight DOC advantage of ~8%. At reduced payloads, the cost advantage falls below 4%, because the conventional airship has to take ballast in order to stay within static heaviness limits. Thus for out-and-return missions, where the airships deliver a rather high payload and return empty, both legs would cost the same when flown with a conventional airship, while the return leg would be less expensive when flown with a hybrid. Such a mission profile would be typical for supply missions or tactical airlift.

While DOC take into account vehicle size, they again don't include the direct value of speed with the associated increase in productivity. Therefore, unit cost UC are typically used [13], defined as:

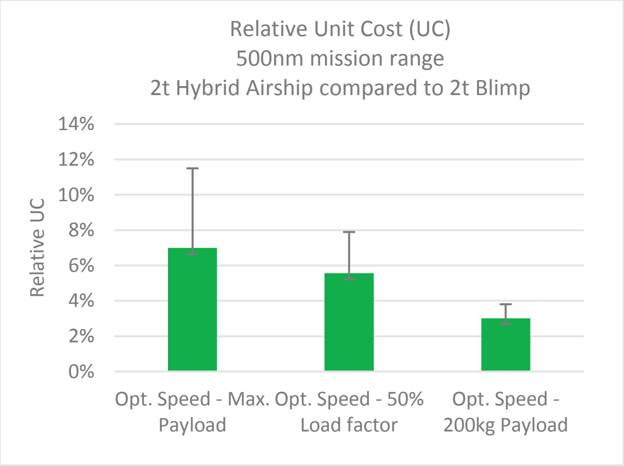
$$UC = \frac{DOC}{SKO}$$

With SKO = Seat kilometers offered = Payload x range x number of flights

Assuming the number of flights proportional to the vehicle speed, unit cost is expressed as:

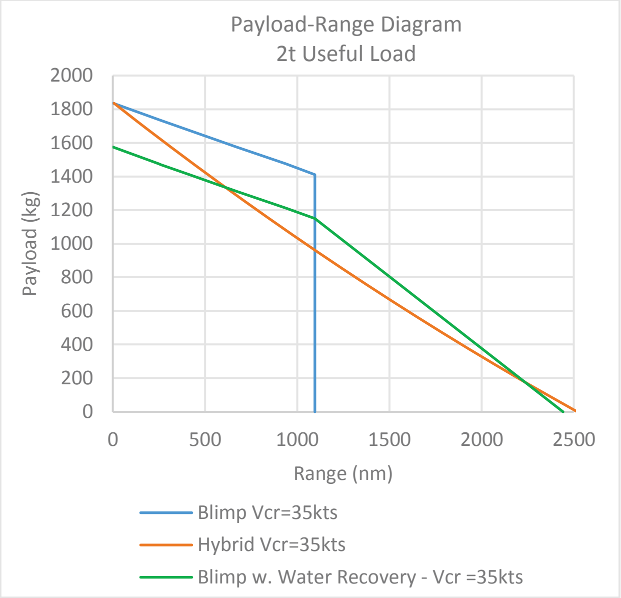
$$UC_{mod} = \frac{DOC}{Payload\ x\ Range\ x\ Speed}$$

Following this definition, the unit cost advantage of the conventional airship is only marginal compared to the hybrid.



11. ADRESSING THE FLEXIBILITY DRAWBACK OF CONVENTIONAL AIRSHIPS

It was shown in the previous chapters, that conventional airships are superior to hybrid airships for missions, where they are not limited by their static heaviness range. This limiting effect of conventional airships is well-known and concepts for overcoming this drawback on airships are numerous. The simplest is venting lifting gas, which, was heavily employed on the hydrogen-fueled Zeppelin airships in the 1920s and 1930s. With today's helium prices at three to five times the price of aviation fuel and overall poor helium availability, this is not an option. A more practical approach is the condensation of ballast water from the combustion engine exhausts, as employed on the last large rigid airships USS Akron and USS Macon. It was also proposed for the LZ-129 sister airship LZ-130. Adding a water recovery apparatus reduces payload and increases fuel consumption, still it can help to make conventional airships very competitive to hybrid airships in terms of payload flexibility:



Concerning productivity, the benefit of increased useable fuel is penalized by the weight and fuel burn increase of the water recovery apparatus, so the hybrid can maintain its superiority. As the water recovery apparatus will increase fuel burn, penalize payload and not improve productivity, no improvement in cost are expected. Past experience indicate, that the apparatus puts a significant additional maintenance burden, so the overall cost impact might well be negative.

12. VEHICLE SUITABILITY FOR DEDICATED AIRSHIP MARKETS

Today there are a few niche markets where airships have found their justification. Additionally, there are some markets for which the use of airship has been proposed.

12.1. Tourist sight-seeing flights

More than 20'000 passengers per year fly around the beautiful scenery of Friedrichshafen/Germany on Zeppelin

NT type airships. This might currently be the largest airship transport market served worldwide. Sight-seeing requires low cruise speed and low flight altitudes, for obvious reasons. To keep tickets prices affordable, average flight time is around 45min, with high load factors. Low operating cost per flight, at full payload is key for a successful business model. Thus conventional airships should have an advantage over hybrid airships for this type of mission.

12.2. Advertising and TV broadcast flights

Of the few markets served by airships worldwide today, advertising and TV broadcast is one, very successfully served by the Goodyear Airship Division. Low flight altitude and low flight speed are required for this type of mission, paired with rather high endurance. For pure advertising missions, payload requirements are rather low. To include TV broadcast, equipment load in the cabin grows quickly. The higher the operating cost, the more expensive the advertising will be to the customer. So the choice would rather be again on the conventional airship due to lower fuel burn, better low speed capabilities and higher payload vs. endurance. Ironically, the smaller size of the hybrid airship can be a disadvantage for this market, since the size of the body represents the maximum size of the advertising area.

12.3. Commercial air transport

Due to its better productivity and competitive unit cost, hybrid airships might prove advantageous over conventional airships as commercial air transport vehicles, be it for scheduled passenger service or cargo transport. As this market is currently not existing, it will have to be developed by the operator. For sure, the hybrid's better payload-range flexibility, flexibility in speed and overall higher range will bring a higher added value to the operator, especially in a developing market with expectable fluctuations in load factors and routes served.

Another advantage to an operator in a developing market is the lower acquisition cost of the hybrid airship and the accordingly lower cost for infrastructure due to the smaller vehicle, which both reduce the financial risk for investors.

12.4. Air supply for rural areas

Typically this mission features rather long range out-and-return flights. Dependent on whether goods are also transported back from the outpost, or it is a pure supply mission, the vehicle might be nearly empty on its return leg. For some of these missions it is even claimed, that accessibility is more important than operating cost. The requirements are long range and some flexibility in payload-range. Hybrid airships should be rather superior to conventional airships on this kind of mission, from a performance point of view. Conventional airships would have to be equipped with exhaust water recovery devices or similar mechanisms to be competitive.

Speed flexibility of hybrid airship is also an advantage for this mission type. It will enable an operator to use smaller weather windows to perform the supply mission, enabling more flights – or any flights at all when facing quickly changing weather conditions.

12.5. Tactical air supply

For tactical military supply missions, the requirements are very similar to those for rural air supply and commercial transport.

The fact that a conventional airship will have to load ballast as it unloads cargo can be considered a disadvantage for tactical air supply, since there simply will be no ballast at the destination, out in the open field. This will put the available range of a conventional airship very low for this kind of mission.

12.6. High altitude pseudo satellites

In the 1950s and 1960s, the US NAVY held a large fleet of blimps, used for submarine warfare and as early warning systems. While those roles were overtaken by other vehicle types, there is continuous interest in using airships as high flying platforms, be it as early warning systems or as cheap(er) alternative for communication satellites.

For pseudo satellites, endurance is the key requirement. Here, the advantage is on the conventional airship, since its lower minimum required power to stay aloft is smaller than for the hybrid airship, even when designing the vehicle for flight altitudes of 60’000ft. Note that in the payload-endurance graphs presented, the hybrid airships endurance at long flight times benefits from the vehicles getting lighter due to burning fuel, which decreases power to stay aloft. This slight benefit will vanish when equipping the vehicles with electric engines powered by hydrogen fuel cells (low fuel consumption) or solar cells (no fuel consumption), as proposed in various studies. Also, the larger size of the conventional airship will allow to install more solar cells on the airship.

13. CONCLUSION

Conventional and hybrid airships show differences in operational performance, even when designed to the same useful load. If the focus is on fuel efficiency, the advantage is on conventional airships, as it is simply more fuel-efficient to generate buoyant lift than aerodynamic lift. Most of today's airship-served markets are of this type, so hybrid airships would have to offer other competitive benefits here.

The increased speed and payload flexibility of hybrid airships comes into advantage when comparing productivity-related parameters. Ultimately, this makes hybrid airships more suited to supply-type missions, as required by military and communities with weak transport infrastructure. As these markets are currently not served by airships, hybrids will have to demonstrate their suitability for these kinds of missions. Key questions would have to address ground infrastructure requirements, rough-weather operability/survivability, and competiveness against other modes of transport like aircraft, road trucks and trains.

Finally, due to their smaller size, the direct and indirect cost of hybrid airships is very competitive to conventional airships. The associated lower financial investment for acquisition and infrastructure could make it attractive for operators to offer hybrid airship services, even if operating cost might be slightly higher than with conventional airships.

14. REFERENCES

[1] G.E. Carichner, L.M. Nicolai Fundamentals of Aircraft and Airship Design, Volume 2 – Airship Design and Case Studies, AIAA Education Series

[2] AIAA-91-1277-CP, J.M. Wright Jr. and R.E. Adams, An empirical method for non-rigid airship preliminary drag estimation

[3] M. Carrión, R. Steijl, G. N. Barakos, D. Stewart, Analysis of Hybrid Air Vehicles Using Computational Fluid Dynamics, JOURNAL OFAIRCRAFT Vol. 53, No. 4, July-August 2016

[4] NACA TN 443, H.B. Freeman, PRESSURE-DISTRIBUTION MEASUREMENTS ON THE HULL AND FINS OF A 1/40-SCALE MODEL OF THE U. S. AIRSHIP "AKRON", 1932

[5] S. F. Hoerner, Fluid-dynamic drag, 1965

[6] AIAA 99-0383, E.J.Saltzman, FLIGHT-DETERMINED SUBSONIC LIFT AND DRAG CHARACTERISTICS OF SEVEN LIFTING-BODY AND WING-BODY REENTRY VEHICLE CONFIGURATIONS WITH TRUNCATED BASES, 1999

[7] NACA TN 432, H.B. Freeman, FORCE MEASUREMENTS ON A 1/40-SCALE MODEL OF THE U. S. AIRSHIP "AKRON", 1932

[8] NACA RM SL 56 A11 M. D. Cannon, STATIC LONGITUDDIAL AND LATERAL STABILITY AND CONTROL DATA OBTAINED FROM TESTS OF A 1/15-SCALE MODEL OF THE GOODYEAR XZP5K AIRSHIP

[9] F.A. Cleveland, "Size Effects in Conventional Aircraft Design", Journal of aircraft Nov. 1970

[10] NASA CR-151920, Goodyear Aerospace Corporation , “FEASIBILITY STUDY OF MODERN AIRSHIPS, Phase II, VOLUME II - AIRPORT FEEDER VEHICLE”, Sept. 1976

[11] NASA CR-151917, Goodyear Aerospace Corporation, “FEASIBILITY STUDY OF MODERN AIRSHIPS, Phase II, VOLUME I HEAVY LIFT AIRSHIP VEHICLE”, Sept. 1976 BOOK I - OVERALL STUDY RESULTS

[12] NASA CR 137692(3), Goodyear Aerospace Corporation, “FEASIBILITY STUDY OF MODERN AIRSHIPS, PHASE I, Volume III- Historical Overview (Task I)”, August 1975

[13] J. Hartmann, “Über das wirtschaftliche Potential und den komplexen Entwurfsraum von Luftfahrzeugen mit hybriden Auftriebskonzepten», 2014

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