Parametric Design of Low Emission Hybrid-lift Cargo Aircraft

Alexander D. Donaldson* Christopher S. Dorbian* Chelsea He* Lishuai Li* Jonathon A. Lovegren* Nikolaos Pyrgiotis* Ioannis Simaiakis*

Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139

I. Nomenclature

\[ C_{df} \] skin friction drag coefficient
\[ K \] induced drag factor of the wing
\[ W_T \] total weight
\[ W_1 \] weight when the fuel tank is empty
\[ n_{pt} \] propeller efficiency
\[ c_p \] specific fuel consumption
\[ V_{ship} \] ship airship volume
\[ S_{wing} \] wing platform area
\[ \lambda_{\alpha} \] ratio of the weight that is supported by the aerodynamic lift to total weight
\[ L_{ship} \] buoyant lift
\[ \Delta W \] weight that is supported by the aerodynamic lift
\[ R \] design range

II. Introduction

A. Motivation

The cargo transportation industry, as it exists today, has two significant gaps in terms of available modes of transportation. Firstly, there exists a large cost-speed gap amongst the different modes of cargo transportation. As depicted in Figure 1, a shipper has the option of either fast and expensive air freight or a combination of slow and inexpensive ship, rail, and truck freight. For overseas transportation especially, there is a need and an opportunity to fill the gap between marine vessels and airplanes. Secondly, there is a large discrepancy amongst current freight transportation modes in terms of environmental performance. The gap between marine vessels and airplanes is again significant, as shown in Figure 2. Marine vessels and rail are relatively clean options compared to the high \( CO_2 \) equivalent emissions per ton-mile output of heavy-duty vehicles and airplanes. The need here is for a freight transportation mode that is greener than airplanes and trucks but more flexible than ships and rail. In this work, we propose a hybrid lift aircraft (HLA) as the solution to these two glaring needs in the cargo transportation industry. A hybrid airship combines buoyant and aerodynamic lift to produce a more efficient and flexible vehicle than the existing aircraft.

*Graduate Student, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139
B. Relation to previous work

Although hybrid aircraft are not a new concept,² there is recently a refreshed interest in hybrid aircraft, partly because of speculation that hybrid airships could serve the aforementioned needs in the cargo transportation industry. Boyd³ introduced the basic equations that govern the performance of hybrid airships and made a case for their economic viability. Liu and Liou⁴ made a more extensive analysis and introduced several designs and candidate missions for a hybrid airship. They presented a set of equations that enabled them to calculate the intrinsic design parameters for their proposed designs. Zhang et al.⁵ improved and completed previous efforts by deriving a set of new formulas that can be used to analyze the steady-state and time-dependent performance of hybrid airships. These equations provide the starting point for the conceptual design of a hybrid airship and the development of computer-based tools for hybrid airship design and optimization.

These academic studies as well as commercial designs, such as the Lockheed P-791,⁶ SkyCat,⁷ or the Aeroscraft,⁸ enable the study and the evaluation of the viability of a hybrid lift vehicle as a potential solution for cargo transportation. The designs in the literature offer only point solutions with little documentation of the exploration of the design space. It is also not clear what the designs attempt to optimize for and what are their competitive advantages compared to other designs.

To summarize, previous work in the area offers a reliable set of equations for the performance analysis and the design parameters of several proposed vehicles. There is a lack of a parametric exploration of different vehicle designs that addresses the various performance tradeoffs across possible solutions. In this work, we generate a series of vehicle designs that perform differently by certain key metrics as a function of variable input parameters. Our goal is to evaluate hybrid airship designs in terms of cost per ton-mile, mission efficiency, and environmental performance as a function of the following inputs: percent heaviness, payload and range. These parameters fully define the design space while the output metrics will serve to demonstrate trade-offs across vehicle designs.

III. Methodology

A. Design Parameters

The design point for each vehicle being modeled was defined by a small set of mission parameters. As with any aircraft design the payload weight drives the size of the vehicle. Maximum range and maximum
cruise altitude were also included as parameters in order to allow modeling of vehicles designed for different missions. As with a conventional aircraft, the primary influence of increasing range on the design is to drive the vehicle size upwards to accommodate the additional fuel requirement. The choice of maximum cruise altitude has a significant impact on the vehicle sizing because operations at higher altitudes require either a larger envelope and ballonets, higher pressure differential between the envelope and the atmosphere or both, all of which would raise the envelope weight. The fraction of the vehicle weight carried by buoyant forces (at maximum gross weight) controls the balance between envelope size and cruise velocity.

B. Assumptions

In order to constrain the design space for this initial architecture study the geometry of the lifting envelope was limited to a single shape. This decision allowed scaling of the aircraft length to be used to control the volume and therefore buoyancy of the vehicle. The NACA 5527 airfoil was used as the basis for the chordwise envelope cross-section due to the large internal volume that it provides. The trailing edge of the airfoil was modified from the standard NACA 5527 to give a more rounded profile, better suited for use as a pressure vessel. The spanwise cross-section was also fixed to be three intersecting pressure vessels as shown in Figure 8. This configuration was chosen for this initial study based upon its use in several previous Hybrid lift vehicle designs. Estimation of the vehicle empty weight is based upon an assumption for the cargo density and calculates the cargo bay volume required for the given payload at that density. The cargo bay dimensions are scaled up to accommodate an even number of a standard LD11 air freight containers (3.2 x 1.5 x 1.6 meters) while also always being able to carry “outsized” cargo as specified by the United States Military. Based on a primary structural configuration of the cargo bay, the Structures Module uses the input payload to size the structural beams to an assumed worst loading case. The cargo bay frame and skin is assumed to be constructed primarily of 6061 Aluminum alloy.

C. Vehicle Sizing and Performance Model

Given that the vehicle shape is fixed in this initial study, the non-dimensional aerodynamic coefficients $C_L$ and $C_{D_t}$ can be pre-computed for a range of angle of attacks using a 3D panel method. A panel method is necessary because of the unconventional shape of the hybrid-lift vehicle envelope, which renders traditional wing lift and drag estimates based on lifting line theory invalid.

For a given set of design parameters a design solution is obtained using an iterative design loop (Figure 3). The first stage in the process involves sizing the envelope appropriately in order to produce the required
buoyant lift. This lift is based on the gross weight calculated from the previous loop iteration multiplied by the specified percentage heaviness ($\lambda_A$). The dimensions of this envelope size estimate are then used to calculate the aerodynamic lift and induced drag on the envelope (from the panel method results) as well as an estimate of the skin friction drag from the Von Karmen Reynolds number relation.\(^9\) The flight velocity that meets the aerodynamic lift requirement while minimizing drag is then calculated as well as the lift-to-drag ratio at this velocity. The envelope size is also used to determine an estimate of the structural weight of the vehicle. The vehicle weight is derived by estimating the weight of the major sub-components of the vehicle. The structural model estimates the envelope material strength requirement by calculating the pressure differential required to maintain structural rigidity and allow for some buoyancy management. The envelope was assumed to be constructed primarily of Vectran, a fabric with high strength and durability. The envelope weight is then calculated from the material properties, maximum stress requirement, and surface area. Figure 4 shows a cross-section of the HLA designed. The cargo bay is sized based upon the payload weight and expectations regarding distribution of loads on the cargo bay floor.

The envelope is sized given the envelope geometry and buoyant lift required. The module estimates the envelope material strength requirement by calculating the pressure differential required to maintain structural rigidity and allow for some buoyancy management. The envelope was assumed to be constructed primarily of Vectran, a fabric with high strength and durability. The envelope weight is then calculated from the material properties, max stress requirement, and surface area. Figure 4 shows a cross-section of the HLA designed. The induced drag factor $K$ and skin friction drag coefficient $C_{df}$ calculated in the aerodynamic analysis are passed into the Breguet Range Equation for hybrid vehicles.\(^4\) The weight fraction from the range equation and structural weight estimate can then be used to calculate a revised gross weight estimate, which is input back into the sizing loop and iterated until a solution is found.

$$R = \frac{1}{\lambda_A} \frac{\eta_{\text{pr}}}{c} \sqrt{\frac{1}{4K C_{df}}} \ln \frac{W_T}{W_{ZF}}$$ \hspace{1cm} (1)

**D. Cost Module**

The Cost Module is the final step in the design tool. It uses the results generated from other modules, including the size, weight, and performance of a specific vehicle configuration, to estimate the operating cost.
associated with that vehicle design. The operating costs obtained from the Cost Module are then used to evaluate all the different vehicle configurations.

In order to simplify the cost calculation only three major costs are included in the model: crew, fuel, and maintenance. Ownership and insurance cost are omitted since the estimation of the vehicle price is out of the scope of this work. The three major cost components are estimated using a set of available information based on current conventional aircraft since detailed data about hybrid airship costs is unavailable. To estimate the crew cost, it was assumed that the pilots are paid an annual salary approximately equal to the average salary of airline cargo pilots ($150,000 including benefits) and that a three-member crew is required to fly the hybrid lift aircraft. The fuel cost is estimated based on the fuel consumption estimate from the vehicle performance model and a reference fuel price ($2.5 per gallon). Maintenance cost is computed by assuming a modified C and D check maintenance schedule and cost based on current commercial aircraft operations. Table 1 summarizes key parameters used in the Cost Module.

<table>
<thead>
<tr>
<th>Crew Cost</th>
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<tbody>
<tr>
<td>Annual pilot salary</td>
<td>$150,000</td>
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<tr>
<td>Flight crew per flight</td>
<td>3</td>
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</table>

<table>
<thead>
<tr>
<th>Fuel Cost</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel price</td>
<td>$2.5 per gallon</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maintenance Cost</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C Check</td>
<td>$400,000 per 2500 flight hours</td>
</tr>
<tr>
<td>D Check</td>
<td>$1.5 million per 7500 flight hours</td>
</tr>
</tbody>
</table>
IV. Results

For each vehicle configuration, the model calculates the fuel burn required for the design mission, as well as the optimal cruise speed for that mission. The percentage heaviness dictates the optimal cruise speed. As the buoyant lift fraction becomes larger the vehicle becomes more like an airship, the envelope grows and its optimal speed decreases. Conversely as the vehicle relies more on aerodynamic lift and the envelope shrinks, the vehicle adopts properties more similar to a conventional aircraft and its optimum speed increases. Thus, percentage heaviness is closely related to optimal cruise speed in all of the following outputs. The most important outputs are plotted below, illustrating some of the performance and cost trends.

![Diagram](image-url)

Figure 5. Relationship between optimal cruise velocity and cost per ton mile for a range of different sized vehicles for a fixed R=6000nm

Figure 5 depicts the relation between the cost per ton mile and the optimal cruise velocity for different vehicle configurations. It can be observed that as the vehicle size increases, the minimum operating cost configuration has a lower $\lambda_A$ and correspondingly lower optimal operating velocity. This effect is due to the distribution of the fixed crew costs for a mission over a larger weight of cargo, giving a lower crew cost per ton mile. This crew cost effect is higher than for conventional air freight due to the low speed correspondingly long crew shifts for the a HLA. Figure 5 also shows that the reduction in cost per ton mile diminishes as the design moves to larger configurations.

Figure 6 shows equivalent CO$_2$ emissions per ton mile based upon the calculated fuel burn from each configuration. When the HLA emissions are compared to those of other cargo transport methods the figure shows that the HLA will be less carbon efficient than a train but more carbon efficient than a truck (at their respective speeds). As $\lambda_A$ is increased (corresponding to an increased cruise velocity) HLA emissions increase rapidly and by 100 kts most HLA configurations are less carbon efficient than traditional air freight.

Evidently, as the payload capability of an HLA increases, the unit operating cost of the vehicle decreases. However, there are certain constraints concerning the operation of a hybrid vehicles that make the choice of the design parameters much more complex than just choosing high payload configurations. There are two distinct operational concepts for a cargo HLA: a) a "door-to-door" service where each operator will transport the cargo directly between factories and distribution centers and b) a cargo service where each operator will...
Figure 6. Relationship between optimal cruise velocity and CO₂ equivalent emissions per ton mile for a range of different sized vehicles for a fixed R=6000nm

fly the HLA via airports or seaports utilizing existing infrastructure and supply chains. Moreover a cargo HLA which can offer both services (e.g. airport to facility) could be valuable to many operators. Choosing the correct balance between payload and accessibility requires a thorough market analysis. Deciding on an optimum design for the chosen service type depends on various factors beyond simply minimizing unit operating cost; some of which are listed below:

- HLA with very large payload capabilities will not be viable if there is not enough cargo to fill them in many of the missions. Such a case may appear especially in a "door-to-door" service where the operator will transfer cargo only between two facilities.

- Operating in airports will set a constraint in the size of the vehicle. Airports with FAA reference code VI (wing span < 80 m) will be able to accommodate HLA with up to 135 metric tons payload capability. A need to operate to a greater number of airports, thus flying in Cat V airports, will further reduce the payload capability to 90 tons.

- Independent of its size, a hybrid aircraft may experience constraints flying into and out of an airport. At a congested airport, an approaching or taking-off airship could significantly affect the throughput of the airport due to its slow speed and longer occupancy time in airspace around the airport. Due to the airships large width and height (in many of these examples, greater than a A380) it may not be allowed to land on certain runways without affecting the operations in other runways and taxiways. Parking space will also be an issue in airports especially with regards to securing fleets of these vehicles.

- Operating from a non-airport location will require a large flat surface near the facility. The availability of area might introduce new requirements to the vehicle such as vertical takeoff and landing (VTOL), which again will limit the size, and consequently the payload of the vehicle. A landing gear that provides the ability to operate on all type of surfaces will also add additional weight.
- Weather resilience has also to be taken into account: Weather avoidance both when parked and while cruising is critical to the operations of a hybrid airship since the airship both flies at low altitude and is susceptible to high winds. As an example a 300-mile detour around bad weather over the pacific can increase the trip time by 5 hours and would require significant amount of fuel reserves. Snowfall may lead to a heavy load applied on the envelope that could cause deformation.

In order to better understand the behavior of the model, a sample HLA design was generated. The Hybird 150 has both water and ground landing capabilities and its width is the same as the Airbus 380, which means it falls under FAA airplane design group VI and thus it can land in any FAA Category VI airport. The range capability is adequate for short transpacific missions, while the design speed puts the vehicle in a niche between cargo ships and airplanes. Table 2 illustrates the design parameters of the Hybird 150.

### Table 2. Example design representing 150-ton HLA.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Hybird 150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Payload</td>
<td>136,000 kg</td>
</tr>
<tr>
<td>Range at Max Payload</td>
<td>5000 nm</td>
</tr>
<tr>
<td>Percentage Heaviness (Input)</td>
<td>0.05 0.5</td>
</tr>
<tr>
<td>Length</td>
<td>123 m</td>
</tr>
<tr>
<td>Width</td>
<td>80 m</td>
</tr>
<tr>
<td>Height</td>
<td>42 m</td>
</tr>
<tr>
<td>Cargo Bay Dimensions (LxWxH)</td>
<td>42mx5mx4m</td>
</tr>
<tr>
<td>Gross Weight</td>
<td>356 tons</td>
</tr>
<tr>
<td>Structural Weight</td>
<td>57 tons</td>
</tr>
<tr>
<td>Payload Fraction</td>
<td>0.42</td>
</tr>
<tr>
<td>Fuel Weight Fraction</td>
<td>0.41</td>
</tr>
<tr>
<td>Aerodynamic L/D</td>
<td>6.4</td>
</tr>
<tr>
<td>Percentage Heaviness (Output)</td>
<td>0.3</td>
</tr>
<tr>
<td>Design Cruise Speed</td>
<td>72 kts</td>
</tr>
</tbody>
</table>

Figure 7. Vehicle dimensions for different payload capacities for R=6000nm and $\lambda_\alpha = 0.2$
Figure 8. Four different views of the example design, the Hybird 150-D.
V. Conclusions

This work demonstrates a process that can be used for the parametric design of an HLA. It shows that the larger the vehicle becomes, the higher the mission efficiency and the lower the emissions per ton mile are. It is of particular significance that the model suggests that any HLA with payload higher than 200 tons can be designed to be operated at a cost lower than 15 cents/ton-mile at a speed of at least 70 knots. This would render the HLA very competitive compared to conventional air cargo aircraft assuming the ownership cost can be kept within reasonable bounds.

Concerning the environmental performance, the HLA can have lower emissions per ton-mile than a truck for a range of speeds and payloads. There are specific designs which can be both faster and produce fewer emissions than trucks. The HLA cannot compete with trains and ships in terms of carbon emissions, but HLAs with design speeds around 70 knots and payloads of 200 tons or higher have half or less the emissions of a conventional aircraft and approximately 3 time the speed of a container ship.

In summary, it appears that HLA with payloads of 200 tons or more can form the backbone of an efficient and low emission cargo transportation system achieving speeds of at least 70 knots at a low cost. Hybrid airships are expected to be considerably faster than boats and lower carbon emitting than airplanes. The ability to overcome manufacturability and operability that will determine the viability of such HLAs. The exploration of these factors comprises part of the future work in this area.

VI. Future Work

The future work is mainly focused in three directions, the first being to refine the current work with more accurate fluid mechanics analysis and a more modular envelope shape. Use of more sophisticated CFD techniques will improve the confidence of the aerodynamic analysis. Further parameterization of the envelope geometry will allow the exploration of the impact of different aspect ratios and envelope configurations. The second direction is to add depth to the market analysis. The recent interest in the hybrid vehicles is due to both the technology enablers (navigation, automation, advanced materials), and the need for a cost-effective and carbon efficient cargo transportation mode to bridge the gap between air and rail/sea cargo. A market analysis is needed to estimate the market size of such a vehicle. Potential markets include electronics, biomedical equipment, oversized industrial equipment, aircraft parts and strategic military airlift. A hybrid airship could be used to transport everything that is too valuable to be transported by boats, but does not have sufficient time-value to be transported by aircraft. An initial market analysis by our team as well as other commercial research indicates that there is potential for a niche market where hybrid aircraft would have a competitive advantage. The third direction is the combination of the market needs with the features and the constraints of such a vehicle to shape some designs that could be successful. For example, the hybrid airship will have difficulty using most airports. On the other hand, a design that will not need an airport, but will be able to land on the sea or unpaved fields will enable point-to-point operations, flexibility and better integration with existing supply chains. Such innovative integration of the HLA into current logistic networks may be necessary for this type of vehicle to achieve its market potential.

VII. Acknowledgments

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