NEXT GENERATION THERMAL AIRSHIP

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ABSTRACT

A novel design for a thermal airship using a rigid, but foldable envelope is described. When not in flight, the envelope can be readily deflated and disassembled for storage and transportation.

Operational advantages of the design include hovering/VTOL operation, minimal ground support and facilities (no hanger or mooring mast) as well as rapid transportation, deployment, and recovery. The structural design promises to be scalable to the levels envisioned by current hybrid proposals. Future refinements and development plans are described.

INTRODUCTION

More than 100 years ago Alberto Santos-Dumont described his vision of an aircraft suitable for a "sportsman of the air." The Skyacht Personal Blimp project pursues an updated version of Santos-Dumont's original vision. The goal of our work is to create a personal recreational aircraft capable of sustained, pleasant, controlled operation with minimal ground equipment and crew. Such a recreational craft will also provide a platform for exploring possible further applications of our designs.

Modern times have brought us many advantages not available to Santos-Dumont. In particular, when Santos-Dumont built his airships (1896 thru 1905) he had little practical choice but to use non-thermal lifting gas, specifically hydrogen. Since that time, technologies have been developed that make hot air practical for recreational flying. In fact, today hot air is by far the preferred choice of lifting gas for recreation flying. Yet, little work has been done towards the design of a recreational airship using hot air as a lifting medium.

Certainly other hot air airships have been and are being developed.[1] However, the intended role of these other projects is typically that of advertising and/or to serve as platforms for aerial photography. The choice of these roles is not surprising; they are the roles filled by most helium airships today. However, the advertising and aerial photography roles have lead designers to make choices that result in craft that are less than suitable for recreational use. For instance, if a ship is to be used for advertising, it needs to operate in a fairly wide variety of wind conditions. Larger propulsion systems and greater demands on piloting skill are the result.

In contrast, pleasure craft can reasonably have fewer performance demands. To paraphrase Santos-Dumont, a sportsman is simply not obliged to fly in unpleasant weather. Operation of pleasure craft can be limited to very light wind conditions, as is done today with recreational hot air balloons. Therefore, the design of pleasure craft can more readily trade off reduced performance for other advantages such as ease of operation.

Another important design distinction is that for advertising (and most other applications), noise emissions (from the engine, prop, etc.) are given far less consideration than is appropriate for pleasure use. The pleasure airship we envision, provides a truly serene experience of flight. Therefore, noise (both inside and outside of the aircraft) is a far more significant issue. The desire to vastly reduce noise during operation has significant structural implications.

Our work has centered on the novel application of classic design principles that use conventional, readily obtained materials and construction techniques. We see the advantages that could be provided through the use of custom made, mission-specific materials. We expect to someday incorporate such materials into future designs. However, we believe that the greatest initial progress can be made by using approaches and design elements that are essentially off-the-shelf.

ENVELOPE DESIGN ISSUES

Most previous hot air airships have been non-rigid pressure ships. Creating a pressure differential inside the envelope of a hot air airship is more problematic than for a helium ship. The envelope of a helium pressure ship is typically sealed. A relatively small blower is used to maintain a desired pressure level. The

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blower on a helium pressure ship does not need to displace much air, only to maintain pressure inside the envelope.

However, hot air airships require a continuous supply of fresh air in order to sustain the combustion needed to heat the lifting gas. The typical approach taken on most previous designs has been to use a fairly large motor-driven pressurizing blower. The inevitable noise created by these larger pressurizing blowers makes such an approach unsuitable for our pleasure craft. An alternative envelope structural approach is needed.

THE RIBBED ENVELOPE

The approach taken on the Personal Blimp uses a foldable, ribbed envelope design. The design allows the ship to carry aerodynamic and structural loads without using pressurization.

Our design employs a novel application of classic tension membrane structural principles. Structures which employ these principles have been in wide use for centuries. Perhaps the most common example is that of the folding umbrella. In all tension structures, the integrity of the structure is maintained by continuously loading various components with opposing tensile and/or compressive forces.

The Personal Blimp envelope structure has three primary components. The first component is the envelope fabric. The fabric has several (typically between 6 and 12) continuous, tubular sleeves sewn into it.

The second component is a a set of slender, deliberately flexible members we call "ribs" that are inserted into the sleeves in the fabric. The ribs themselves are usually hollow tubes. Prior to inflation, the ribs are straight. The fabric of the envelope is shaped such that the tips of the ribs ribs are held closely together.

At the convergence points of the two sets of tips, the third component, a tensioning line is attached. When the envelope is inflated, the tensioning line runs along the central longitudinal axis of the envelope.*

The envelope is inflated by winching the tensioning line to make it shorter. As the length of the the tensioning line decreases the ribs are forced to bend or "bow" outward (See Fig 1. and Fig 2.) To be more specific, the ribs deform by first order elastic buckling. The winching process continues until the envelope fabric is pulled taut. Inflation can be assisted by using a ground based inflation blower. The blower, while helpful, is not strictly necessary. In any case, once inflation is complete, the blower is turned off and the structure is statically self-supporting.

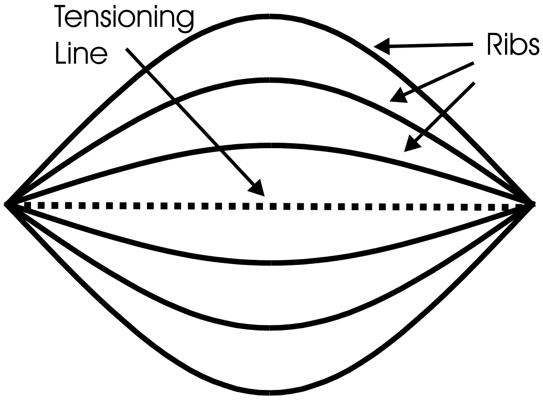

Fig.1

Side View of a Ribbed Envelope ("Football" Shaped)

The "natural" shape of these structures (using ribs of uniform cross section and fabric cut to allow the ribs to bend in an unconstrained manner) is a pointed oval shape - roughly the shape of an American/Canadian-style football or a slightly more pointed shape than a Rugby ball.

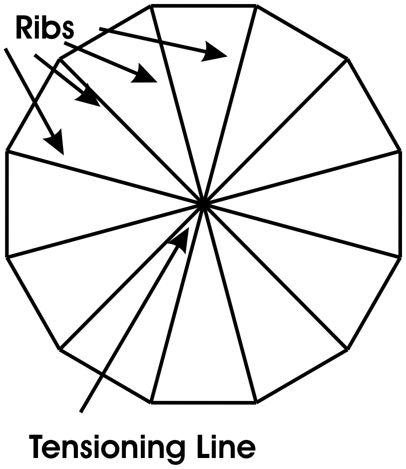

Fig. 2

End View of a Ribbed Envelope

Rather than being a smooth shape, a ribbed envelope is faceted. The edges of the facets run longitudinally with a rib running along the the edge of each facet. For

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*One can optionally attach a rigid end cone structure at the tips of the ribs or simply hold the tips together using the envelope fabric itself. In practice we tend to use small rigid end cones.

short, we will refer to this type of structure as a "ribbed envelope".

For deflation, the tension on the central line is released and the ribs naturally resume their original straight shape. Contrary to what one might expect, the envelope does not snap closed as an umbrella does. In fact the closing of the envelope can be controlled quite precisely. We describe deflation in a later section.

In simplified terms, it can be helpful to think of a ribbed envelope as essentially a pair of gigantic umbrellas. The umbrellas are oriented such that their "tops" are pointing in opposite directions. The fabric and ribs of these two fictitious umbrellas run continuously. The tensioning line replaces the "handles" of the umbrellas being hooked together.[*]

Another way to consider the structure is to identify the forces at work in the components. In the case of our ribbed envelope, the ribs are held under compression. The opposing forces are to be found in the envelope fabric and tensioning line which are held under tension.

Tension structures provide excellent structural support for a given weight. For instance, one of our model envelopes measuring 7.6 meters long by 5.2 meters in diameter encloses a volume of approximately 100 cubic meters with a structural mass of only 10 kilograms.[†]

In addition to providing a lightweight, sturdy, statically self-supporting enclosure for the lifting gas, a non-pressurized, ribbed envelope provides other advantages over a pressurized design:

- Envelope fabric stresses are reduced because no force is needed to retain the pressurized gas. This is particularly true around the waist of the ship where the "ring tension" due to pressurization is the greatest.

- Providing a supply of fresh air to feed the heaters is simplified because there is no pressure gradient to overcome. One particularly interesting possibility to consider is the use of Venturi burners[‡].

- The nose and tail cone provide convenient "hard points" for attaching propulsion and maneuvering systems.

- The ribs also provide excellent attachment points for other structural components such as tail fins.
- The ribs provide an excellent means of distributing loads to the envelope. Envelope distortions due to point loading are greatly reduced or eliminated.

- In calm conditions, the aircraft can be set up and left standing for easy inspection, as well as the installation and maintenance of other systems. This is particularly helpful for a design such as ours that is undergoing active development.

An Improved Shape - The Teardrop

Although the default shape of the ribbed envelope described above will be a that of a longitudinally symmetric football, other shapes are obtainable. The buckling of the ribs can be constrained by the shape of the envelope fabric. However, if the shape of the envelope fabric differs widely from the default shape, then the resulting structure may become unstable.

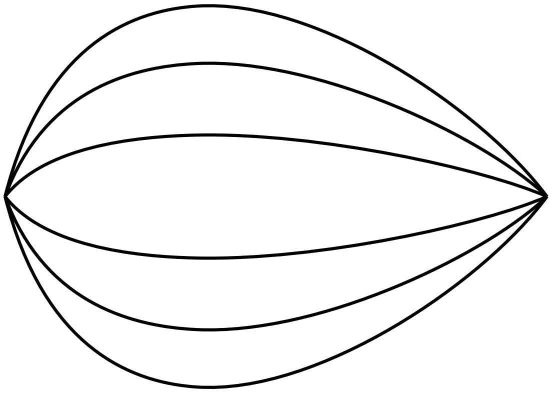

Fig 3.

Side View of a Teardrop Shaped Envelope

One shape of particular interest is an asymmetric pointed oval shape. We'll call this shape a "teardrop" The teardrop shape differs from the football shape in that the forward portion of the envelope is more rounded than the rear.

The teardrop shape has several advantages to over the football shape. Most important is the amount and location of structural support provided by the ribs. The load carrying capacity of the ribs is related to their radius of curvature. A portion of rib with a large radius of curvature (less buckled) will support less load than a portion of rib with a smaller radius of curvature (more buckled).

The teardrop shape is better matched to the aerodynamic loads experienced in flight. In the default

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[*] We would like to thank Donald Doolittle for bringing the umbrella analogy to our attention.

[†] In American units, the model is 25 feet long by 17 feet in diameter and encloses 3,300 cubic feet and weighs about 21 pounds.

[‡] Venturi burners use the force of the expanding combustion gases as the means of drawing outside air into the combustion chamber.

football shape, the midsection of the ribs has the smallest radius of curvature with the radius increasing gradually towards the ends. Unfortunately, this does not well match the aerodynamic loads applied to the envelope. In particular, it is near the nose of the envelope where positive aerodynamic loads are the greatest. The teardrop shape provides more efficient support by ensuring that the ribs have a relatively small radius of curvature along the entire length of the nose.

The second advantage of the teardrop comes from the relative elongation of the tail. We expect that the more gradual slope of the tail portion of the envelope will improve aerodynamic performance. The expected improvement will come from improved convergence of the air streams as they pass over the tail. In addition, we expect that the reduced curvature along the tail will delay separation of the air streams from the envelope.

Structural Response to Excessive Loading

One of the advantages of tension membrane structures with slender members is the predominance of "graceful" rather than catastrophic failures. Typically, when such structure is overloaded structural "failure" does not take the form of component fracture or plastic deformation. Rather, one or more of the components under compression will buckle in one of their higher order bending modes.

The usual failure scenario takes the form of deformation(s) of the ribs into their second order bending modes. Entering second order bending relieves the stresses on the various envelope components. Like the first order bending used to create the initial envelope shape, these higher order deformations are also typically elastic. As such, once the excessive loading is removed, the envelope reverts back to its original shape. No permanent damage is done.

Given sufficient loading, it is possible to cause plastic deformations or fractures in the envelope components. It is almost always the case that ribs fracture. In particular, for storage and transport reasons, the ribs are composed of coupled segments.* Failure of the ribs almost always occurs at the coupling joints where stress concentrations typically occur.

We are encouraged to note that during construction and testing of our larger models (with ribs lengths of 8 to 10 meters) we have rarely been able induce fracture failures. However, when fractures do occur, the overall integrity of the envelope remains essentially undiminished. In several cases, we have not even detected that a fracture has occurred until the envelope was disassembled and inspected.

As with the onset of higher order bending, a fracture failure of one or more ribs typically relieves the stress placed on the other components rather than increasing those stresses. As a result, even after many earnest attempts, we have never been able to induce a catastrophic or cascading structural failure in any of the model envelopes.

This graceful failure behavior relies on the relative flexibility and slenderness of the ribs in contrast to the strength of the envelope fabric. Should future designs incorporate significantly stiffer and stronger ribs, for instance in an attempt to obtain greater aerodynamic load carrying capacity, great care will need to be taken to ensure that the envelope fabric is not then subjected to forces sufficient to induce catastrophic failures.

Safeguards Against Uncontrolled Deflation

As mentioned above, the envelope is deflated by releasing the tension on the central line. As a safety concern, one needs to consider what happens if the central tension line fails. The answer is that little, and sometimes nothing, happens.

As mentioned above, envelope deflation is a gradual rather than a sudden process. There are several factors that cause this to be the case.

Most importantly, in order to deflate, the gas inside the envelope must somehow move through the surface of enclosing fabric. Therefore the rate of closure can be controlled simply by the opening and closing of vents in the envelope fabric.

Secondly, because the envelope is faceted, the envelope fabric itself can be used as a substitute for the central tensioning line. In particular, a curved line drawn along the longitudinal center of a facet is always shorter than a curved line that follows the edge of facet. The ratio of the facet edge length to the facet centerline length is inversely related to the number of facets in the envelope.

The necessary tensioning force can be placed on the ends of the ribs merely by adding a structural element (such as a line) that limits the distance that the ends of the ribs can move from the centerline of the adjacent

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*Since the ribs are loaded under compression, the segments face essentially no risk of coming apart once the envelope is inflated. That said, the ribs are typically hollow tubes and a "safety line" is run inside the ribs on the unexpected chance that they are somehow put under tension.

facet(s). Loading the envelope facets along their centerlines in this fashion will cause them to deflect inward. When so deflected, the facets are slightly concave rather than flat. As such, the volume of the envelope is somewhat reduced.

Given the reduction in volume caused by the concave deformation of the facets when loaded longitudinally, the fabric is typically not used as the primary longitudinal tension member. However, its ability to act as such provides redundancy to the structure.

There is a third means of ensuring that the envelope can not deflate accidentally while in flight. Specifically, the weight of payload(s) can also be arranged so as to offload the central tension line. This arrangement is described in detail below.

Tail Fins

We expect to use tail fins in our design in order to provide aerodynamic stability as well as damping of any roll, pitch, or yaw oscillations that occur. Although we do not expect to use control surfaces in our design, the fins could also be used as attachment points for them. Since the envelope is designed for ready inflation and deflation it is important that the fin structure fold and unfold as well.

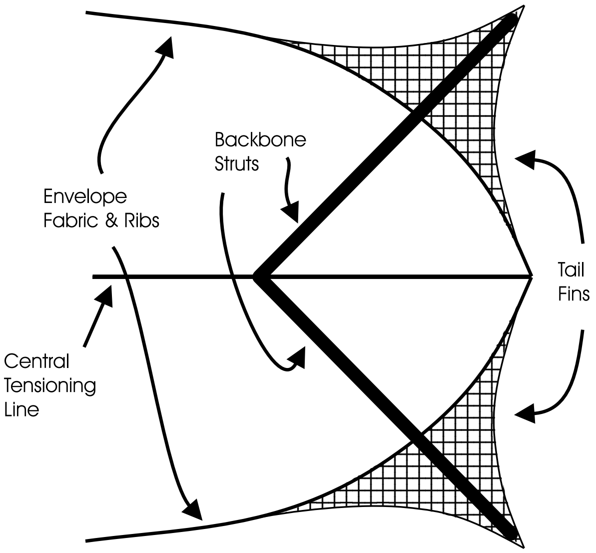

Fig. 4

Cross sectional view of envelope showing tail fin construction.

The "umbrella" analogy of our ribbed envelope design suggests a straightforward approach for a fin design. Almost all umbrellas have struts that run from the member along their central axis to the ribs along the fabric surface. The fins attached to our ribbed envelope can be implemented by incorporating comparable struts. However, rather than having the struts terminate at the fabric surface (as they do in an umbrella), the struts are extended through the fabric of the envelope. Each extended strut is then used as a backbone for a fin.

The fin surface itself is formed by a roughly triangular piece of fabric. One edge of the triangle is attached to the main envelope surface adjacent to the line of one of the ribs. The opposing vertex of the attached edge is itself attached to the far end of the extended strut member. When the triangle of fabric is pulled taut along the backbone member it forms a web that is slung between the tip of the backbone member and the main envelope fabric. Even tension along the width the fin fabric can be obtained by giving the unattached edges a catenary (scalloped) shape.

Load Support System

Of course, the ultimate purpose of any airship envelope is to support the weight of some payload. A ribbed envelope structure provides two advantages over conventional pressurized envelopes as a means for supporting loads.

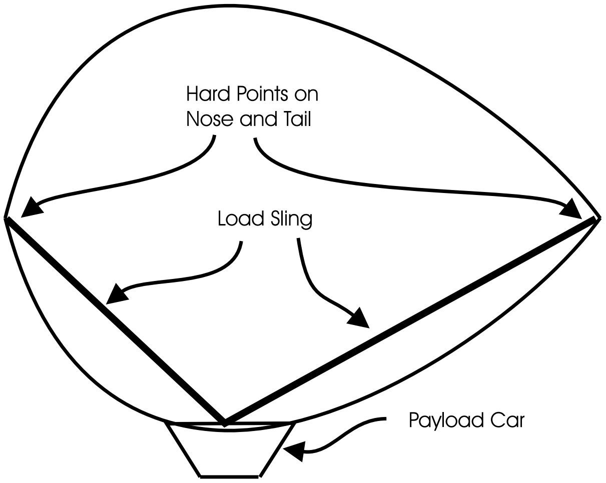

Fig. 5

Cross sectional view of envelope showing a load sling configuration for a single payload car.

The first advantage applies to the use of a conventional load curtain running vertically between the top of the envelope to one or more payload cars at the bottom. A consistent design challenge facing any load curtain configuration is the deformation of the envelope from loading. Such deformations can be local or overall in nature. Local deformations consist of a puckering of the envelope fabric at the point where the curtain attaches. Overall deformations consist of the bending and creasing of the entire envelope due to loading.

In our ribbed envelope structure, the ribs provide very effective locations for transferring loads from the load curtain to the envelope. The stiffness of the ribs, in concert with the membrane tension, resist both local and overall deformation. Puckering at the attachment points is essentially non-existent. Similarly, there is much less need to "fine-tune" the curtain loads in order to avoid overall envelope deformation.

In short, our approach enables localized or point loads to be distributed broadly across the envelope. In some cases, loading actually increases the structural efficiency of the envelope.

In particular, a ribbed envelope provides a second and unique means of carrying loads. As mentioned earlier, the convergence of the ribs at the nose and tail provide excellent hard points in the structure. The weight of the payload is readily transferred to the envelope at these hard points. The most straightforward method to accomplish this is through the use of a set of lines that run from the payload car to the nose and tail hard points. These lines form a "load sling" that supports the payload weight.

In addition to supporting the weight of the payload, a load sling is also useful in handling the longitudinal forces created by forward and rearward surging of the payload. These longitudinal surging forces can include inertial forces, forces caused by the car being in contact with the ground, as well as the force associated with car mounted propulsion systems.

With a conventional pressurized envelope, these longitudinal loads are mainly transferred to the envelope via load patches on the envelope fabric. Much design and construction effort focuses on these patches. With a load sling, these loads are carried primarily by the natural shifting of loads between on the front and back sections of the sling. By avoiding placement of stresses on the envelope fabric, envelope fabric weight can be reduced and the construction simplified.

Another opportunity provided by a load sling arrangement is the partial or complete offloading of the central tension line while in flight. The offloading effect is shown in Fig 6. For the purposes of this analysis, we will neglect the weight of the envelope itself and assume that the airship is at aerostatic equilibrium.

The force that the load sling and the envelope fabric apply to the end cones can be decomposed into vertical and horizontal components. The vertical component of the force along the envelope fabric is exactly the lifting force of the gas. Likewise, the vertical component of the force from the load sling is the weight of the payload. Since the aircraft is at aerostatic equilibrium, these forces must be equal. Thus the net vertical force on the end cones is nil.

What remains are the two horizontal components. It is interesting to note that these horizontal components align precisely with the tension forces applied by the central tensioning line. Therefore, as more weight is place on the load sling, the force required of the central tension line decreases. In fact, if sufficient load is applied to the load sling the central rope goes completely slack.

Clearly the amount of load that can be carried by the load sling is limited. That limit is determined by the total stiffness of the ribs and the tensile strength of the envelope fabric. Given the slender ribs used in our designs to date, the limiting factor has been the stiffness of the ribs. Therefore, if the horizontal components of the payload weight and lifting force combine to exceed the initial tension in the central line, then the ribs begin to deform. From experiments with models, the deformations are gradual and take the form of second order elastic buckling of the ribs.

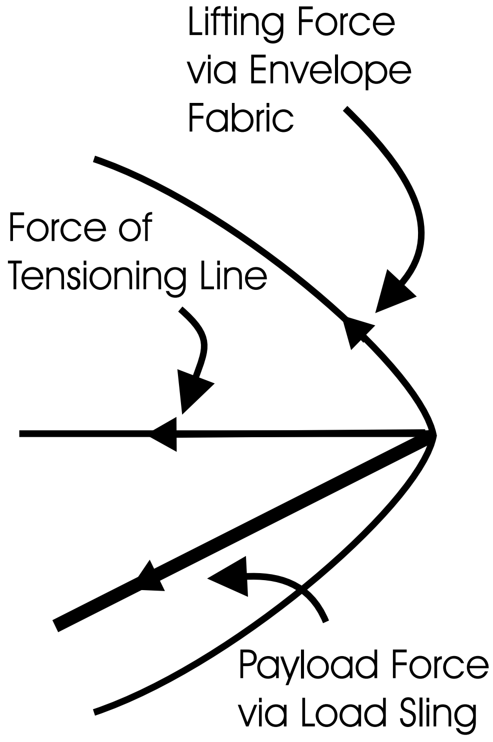

Fig. 6

Forces applied to an end cone by the load sling, envelope fabric, and tensioning line

To date, the force applied by the central tensioning line is fairly low when compared with the weight of the payload. Therefore, not all of the load can be carried via a load sling. In order to fully support the weight of the payload both a load sling and a load curtain are used.

The amount of structural support needed to handle the aerodynamic loads at the relatively low airspeed of our application allows the use of relatively flexible ribs. However, designs requiring higher airspeeds will necessarily require relatively stiffer ribs. The resulting increase in rib stiffness raises the intriguing possibility of eliminating the load curtain and relying completely upon the load sling for payload support.

Mathematic Model of Structural Support

As part of our development approach we will be implementing scale models of various envelope structures. We plan to experimentally determine the aerodynamic and other loads that the models can withstand. We can then use a mathematical model to determine the effect of scale on structural capacity.

In our design, the ribs and the membrane tension in the envelope fabric are the primary structural features. Our designs use standard hot air balloon fabrics. These fabrics have excellent tensile strength characteristics. As a result, for the range of sizes we plan to implement, the ribs are the limiting load-carrying structural elements. So we will focus our analysis on the ribs.

We will assume that the envelope configuration (number of ribs, overall shape, etc.) and material of the ribs remains unchanged throughout our analysis. We will also assume that the ribs are made up of thin-walled hollow circular tubes.

We will attempt to develop a mathematical model that captures two relationships. First, we wish to determine how much the cross sectional radius of the ribs must be increased in order to maintain structural support as the size of the envelope is increased. Secondly, we are interested in determining how much the cross sectional radius of the ribs needs to be increased in order to support the aerodynamic forces of increased airspeed.

Increased Scale

Obviously as the scale of the envelope increases, the forces placed on the ribs also increase. We will assume that the aerodynamic pressures remain constant irrespective of airship size. Therefore the total load supported by each rib will depend upon the amount of envelope fabric it must support. Since the surface of the envelope will increase as the second power (square) of the envelope scale, the force that must be supported by a given rib will also increases as the square of the scale.

Next we consider the ability of the ribs to support loads. We model the ribs' behavior by treating them as curved beams of large curvature. By large curvature we mean that the maximum "height" of the arch formed by the ribs (i.e. the girth of the envelope) is very much larger than the cross sectional radius of the ribs. As described earlier, the ribs are already placed in their first order buckling mode and structural "failure" takes the form of higher order buckling. So we are interested in the force required to induce the next higher order buckling mode.

The ability of curved beams of high curvature to resist elastic buckling depends upon several factors:

- the Elastic Modulus of the beam material
- the length of the beam
- the cross section of the beam
- the initial curvature of the beam

We will consider each of these factors in turn.

As mentioned above, for this analysis we assume that the beam material stiffness (as typically represented by the material's Elastic (Young's) Modulus) remains unchanged. We will note only that the capacity of these curved beams is linearly related to the material stiffness. In other words, doubling the material stiffness will double the force that can be placed on the beam before buckling. Therefore we are encouraged by the progress currently being made on a broad front towards producing high stiffness composite materials.

As for beam length, the ability of a beam that is in a given state of curvature as well as being of a given cross section and composition to resist buckling is inversely proportional to the second power (square) of the length of the beam.[2] In other words, all other things being equal, if a arched beam of a particular shape has its span increased by a factor of 2, then the force needed to buckle it is reduced by a factor of 4.

The last factor to consider is the cross section of the beam. As mentioned above, we will limit our discussion to beams with a hollow circular cross section (i.e. tubes) The important attribute of a particular beam cross section is the Moment of Inertia. For hollow thin-walled circular cross sections, this value is $\pi r^3 t$ where r is the average tube radius and t is the thickness of the tube wall.

As described, the stiffness of the beam increases linearly with wall thickness and as the third power (cube) of the average radius of the beam. The weight of a beam will increase linearly with both the wall thickness and the beam radius. So the maximum stiffness for a given amount of weight is obtained by using a beam of minimum wall thickness and maximum radius. As a practical matter, the minimum wall thickness is determined by the manufacturing processes for a given material.* Therefore, we will assume that the wall thickness will be held constant for the range of sizes we are considering.

To combine the factors above, the loading of the ribs increases as the square of the scale. Also, the ribs' ability to resist buckling decreases as the square of the scale. Therefore, in order to support constant aerodynamic pressures, the ribs' overall stiffness needs to increase as the fourth power (square times square) of the scale. Since the stiffness of the ribs increases as the third power of their cross sectional radius, the necessary load carrying stiffness can be obtained by increasing the rib radius as the 4/3 (1.33) power of the scale. So, if the scale of a ribbed envelope is increased by a factor of 2, then the radius of the ribs must be increase by a factor of 2.51 ($2^{4/3}$).

Since the weight of the ribs increases linearly with the rib radius as well as linearly with the the rib length, the overall weight of the ribs will need to increase at the 7/3 (1 + 1.33 = 2.33) power of the scale. For example, if the scale of a ribbed envelope is increased by a factor of 2, the weight of the ribs will increase by slightly more than a factor 5.04 ($2^{7/3}$).

This is a fairly encouraging result. The weight of most elements of an envelope increase at the square of the scale. We could have hoped for no better for the ribs. Since the gross lift of an envelope increase at the third power of the scale, the relative weight of the ribs decreases as the scale of the envelope increase. As is so often the case, an increase in size leads to an increase in airship efficiency.*

Increased Airspeed

Since at these high Reynolds numbers aerodynamic forces increase as the square of the relative wind speed, the forces applied on the ribs will likewise increase as the square of the relative wind speed. As we have seen above, the stiffness of the ribs increases as the cube of the ribs' radius. Therefore, the cross sectional radius will need to be increased as the 2/3 (0.66) power of the airspeed. For example doubling the maximum operating airspeed will require that the rib cross sectional radius be increased by a factor of 1.6 ($2^{0.66}$ = 1.6). Since we assume that the weight of the ribs increases linearly with the rib radius, the total rib weight will also increase by a factor of about 1.6 for each doubling in airspeed.

It should be remembered that, like a pressurized envelope design, the tensile loads on the envelope fabric for a ribbed envelope increase as the second power (square) of the airspeed. Thus, the overall weight of a ribbed design (ribs plus fabric) will increase, at worst, somewhere between the 2/3 power (for the ribs) and the second power (for the fabric.) The precise rate of increase will be determined by the relative contributions of the ribs and fabric to the overall weight.

OTHER DESIGN ISSUES FOR OUR INITIAL DESIGN

Car Location and Ground Handling

It is very convenient to have an airship design that is statically-stable and self-supporting while on the ground. Such a design provides an easily accessible platform for system installation and maintenance. Therefore, we do not expect to use a conventional single car configuration. Unless a single car were extremely broad and long, the ship would be unstable when on the ground. As a result, the envelope would tilt and come into contact with the ground.

We intend instead to use 3 cars. One car is located forward of midpoint. The other two cars are located aft of midpoint of the ship. The two rear cars are set to the sides to the centerline of the ship along the edge of the envelope facet on the bottom of the ship. Given this arrangement, the three cars form a stable tripod on which the envelope can rest. When in flight, the forward car holds the pilot and passenger(s). The rear cars hold other components (see below).

Propulsion and Steering

Since a primary goal of our design is to provide as serene an experience of flight as possible, we need to consider unconventional propulsion systems. Conventional piston driven propeller systems are simply far too noisy for our application.

Fortunately, electric and hybrid-electric systems have much to offer in this regard. For example, a self-launching motor-glider, named Antares, has been built with a propulsion system consisting of a low mass (31 kg) electric motor and a large diameter (2 meter) slow-

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* This is particularly true for the polymer/carbon-fiber composites we have been working with thus far.

*We will note again that we have assumed that the wall thickness of the hollow ribs has remained unchanged. Clearly this assumption can not hold for designs of a very large scale. However, we do not expect that increased wall thickness will be a significant issue.

speed (1500 RPM) propeller. This configuration reportedly produces 56 horsepower with noise emissions of less than 40 dB.[3] The Antares propulsion system serves as an example of a system that produces significant thrust with minimal noise.

The limiting factor in the application of such systems is the production of electric power. In the case of the Antares, the power is provided by battery packs. Clearly battery based systems are impractical for an airship. However, the current production of hybrid-electric automobiles promises active and continuing development of portable electric generation systems.

Propeller Placement

In our design, two obvious locations for propulsion propellers exist. The first is the more or less conventional location of attaching the propellers on the car(s). The second location is the less conventional location at the tail of the envelope. We will not delve into general design issues of these two propeller locations.

We will note however, that in our design, the tail-mounted location is more appealing than usual for two reasons. First, in virtually any design, tail mounted propellers tend to help the air stream reconverge. This issue is quite important in our case given the relatively low fineness ratio (1.4 to 1)[*]. Second, a ribbed envelope structure, with its hard points on the tail and with the ribs serving as radially oriented support members, makes mounting propellers significantly easier than on a fabric-only envelope.

Steering, Stability, and Trim

Yaw Control and Steering

Given the relatively low operating airspeeds for our design, we would expect little control authority from a rudder, unless it is very large. Therefore we do not plan to incorporate one in our initial design. Instead differential and vectored thrust from the propulsion props is used to steer the ship. The placement of two control cars at points well away from the centerline of the ship makes this approach easier to implement.

Another alternative steering mechanism that we expect to implement over time is to locate a pair of propellers near the tail of the envelope. These two propellers will be offset on opposite sides of the centerline. Differential thrust from these tail-mounted propellers will be used in a manner similar with the car-mounted system described above.

We expect that yaw stability to be provided by tail fins. Further, the tail fins should dampen any yaw oscillations that arise.

Pitch Control

As with steering, we anticipate an elevator to be of little use at the airspeeds our design will be operating. Fortunately, we foresee little need for pitch control in our application. We intend to rely upon a combination of pendular stability and the damping effect of the tail fins to limit any pitch oscillation. It should be noted that given the low operating airspeed and the low fineness ratio of our design, we expect pitching moments to be relatively minor.

Roll Control

Similarly to pitch, we anticipate minimal need for roll control. As with pitch, we expect static (pendular) stability to be the dominant factor. Likewise, the tail fins are expected to provide sufficient damping of rolling that occurs.

NEAR TERM FUTURE DESIGN DIRECTIONS

The designs described above are embodied in our initial configuration that is currently under construction. We expect that once work on this initial craft is completed, it will serve as a platform for other development directions. We describe some of those directions below.

Non-blast Heaters

The typical mode of operation of hot air balloon heaters is commonly referred to as "blast" mode. Blast mode heating means that the heaters are operated at fairly wide intervals (somewhere around 1 minute) and put out enormous amounts of heat (most balloon heaters produce tens of millions of BTU's per hour) for only very short periods of time (usually about 5 seconds). The primary disadvantage of blast-mode heaters is the large amount of noise they create (at least 90dB.)

Blast-mode operation has evolved as the primary method for controlling a hot air balloon for good reason. The ability to produce rapid heating of the lifting gas gives pilots much more control of ascent and

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[*] The fineness ratio is the relationship of the length of the ship to its width. Discussions of winged aircraft typically refer to an aspect ratio (width/length) which is the inverse of fineness.

descent rates. In particular, a blast-mode heater allows a pilot to make a rapid descent over an obstacle and then promptly decelerate or "flare" when close to the ground.

Except under emergency conditions, we do not expect our airship to make rapid descents over obstacles. Therefore blast mode heaters offer little advantage for our design. We will initially use blast-mode heaters because of their wide availability and excellent track record of reliability. However, we expect to replace or at least supplement them with quieter heaters over time.

Envelope Insulation

One of the obvious disadvantages of using hot air as a lifting gas is the additional fuel required to compensate for heat loss through the envelope. The problem is more severe for an airship than for a balloon because the movement of air over the exterior of the envelope significantly increases heat loss.

To date, most hot air balloons and hot air airships use a very simple, single-walled, uninsulated envelope. Some success has been reported with designs that reduce heating fuel requirements by insulating the envelope. The most frequently adopted approach, often used on designs targeted on setting records, uses a double-walled design. Air trapped between the two layers of fabric serves as an fairly effective thermal insulator.

The second approach is to use fabrics that are themselves more effective thermal insulators than the standard balloon fabrics. Other investigators have reported reducing heat loss by a factor of 3.4 using insulating fabric with an added mass of only 133 g/m2.[4]

We intend to pursue both the double-walled and insulating fabric approaches in the near future.

LONGER TERM FUTURE DESIGN DIRECTIONS

The development directions mentioned above relate to the airship currently under construction as well as the steps we expect to take with it in the near future. However, we see avenues of investigation that go well beyond these near term designs.

Some of the possibilities mentioned below are fairly straightforward. Others are clearly far fetched. We include them here not so much as a blueprint for further work but rather to show some of the new avenues of possibility opened by a consideration of thermal lift in airship designs.

More Complex Internal Structures

We chose the envelope design described above because it employs the simplest possible tension structure. However, we envision several more complex structures that may well prove to be more efficient than the current "minimalist" configuration.

Our design will clearly suffer in terms of aerodynamic efficiency due to the its low fineness ratio of about 1.4. We chose a "stout" design for the reasons of static and aerodynamic stability described above. In addition the ribs (compression members) are effective as structural supports only when they are significantly buckled. A radius of curvature that is too large leads to an unstable structure.

Two strategies present themselves to create structurally stable envelopes of a higher fineness. Firstly, the stiffness of the individual ribs can be increased. Such an increase in stiffness can be accomplished, for example, using stiffer materials and/or ribs of a larger diameter, and/or tension truss structures. At present, we are planning to use ribs that are carbon-fiber/epoxy composites. We believe that this material already represents the best combination of weight, stiffness and cost. We are also using ribs with the largest readily available diameter.

Longitudinally Compound Designs

An alternative approach is to create a compound structure that combines two or more of the basic tension structure elements found in our initial design. By attaching two or more of these elements longitudinally, the fineness ratio of the overall envelope can be increased without increasing the radius of curvature of the individual ribs.

Laterally Compound Designs

A further design extension involves attaching two or more sets of longitudinally compound ribs in a side-by-side manner. This approach yields a wider shaped envelope with intriguing possibilities for creating more efficient aerodynamic lift. It is interesting to note that the shape of such a double-compound design is very similar those proposed for aerodynamic/aerostatic hybrids.

Nested Structures to Support the Nose

Another possible area of structural improvement to be addressed is the handling of aerodynamic loads on the forward portion of the envelope. Like any roughly ellipsoidal envelope, the greatest loading per unit of area occurs at the very nose of the craft. However, the point of greatest structural loading of the ribs occurs well back from the nose. This arises because the load at a given point on a rib is a product of the air pressure per unit of area multiplied by the distance separating the ribs. Providing additional support at this point of maximum rib loading should increase overall structural efficiency. We see two ways to provide this support.

The first approach is to use struts of the form that are commonly employed in almost all umbrellas. Placement of the struts at the point of maximum loading of the ribs will add support where it is is needed the most. We are concerned however that the use of such struts will inevitably create significant stress concentrations where the struts join with the ribs.

Alternatively, we might consider adding a second but smaller ribbed ellipsoid inside the nose of the ship to better carry the aerodynamic loads. The ribs of the inner ellipsoid would be curved much more than the ribs of the outer (main) structure. This second ellipsoid has the advantage of avoiding stress concentrations. Further, the inner elliptoid can be made large enough so that support is provided throughout the region of maximum positive aerodynamic load.

Internal Catenary Support Webs

One way to increase the rigidity of the ribs is through the addition of internal catenary support web (See Figs 7 and 8.)

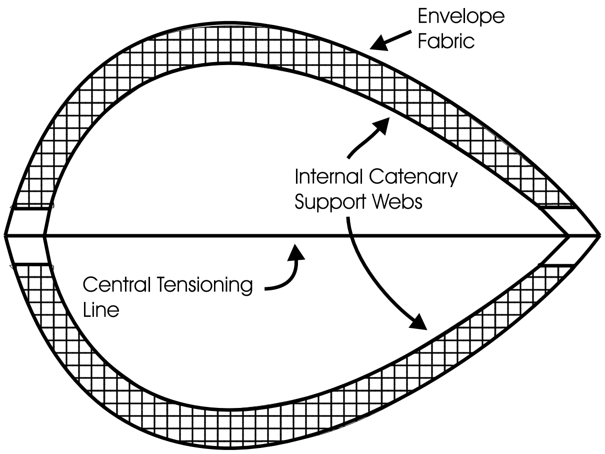

Fig. 7

Side Cross Section of Envelope with Intenal Catenary Support Webs

In such an arrangement, a set of longitudinally oriented fabric webs is added inside the envelope. One edge of each web is attached to the envelope immediately adjacent to each rib. Into the other edge of each web is sewn a sleeve. A catenary tensioning line runs inside each sleeve. These lines are used to place the fabric of the webs under tension after the envelope is inflated.

With the catenary tension lines pulled taut, the webs of fabric are also placed under tension. When the entire structure is then placed under load, much of the outward forces exerted on the ribs are carried through the fabric webs and then to the catenary tensioning lines.

By offloading the ribs in this manner, higher overall loads can be carried by the structure. In addition, the tension applied to envelope fabric by the outward force of the ribs at the midpoint of the ship can be greatly reduced.

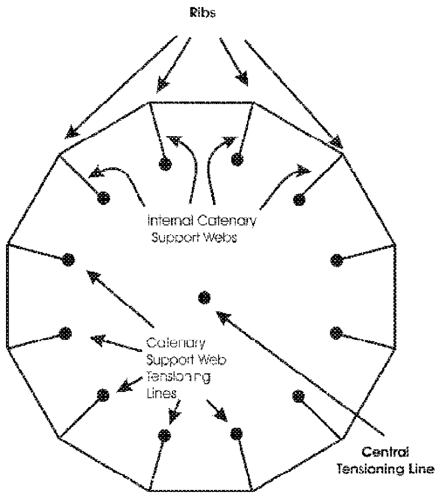

Fig 8

End View of a Cross Section Made near the Midpoint of an Envelope with Internal Catenary Support Webs

Rigid and/or Solid Envelope Segments

Another structural direction is to be found in the use of rigid and/or solid segments as part of the envelope. In our initial design, the ribs are quite slender and distinctly flexible over their entire length. One might consider making some portions of the ribs (particularly the nose) of much greater rigidity. An even bolder step would be to construct the forward portion of envelope out of solid panels rather than fabric. The panels would be arranged as hinged pairs between each rib. As the envelope is inflated/deflated the panels would open and close in a manner analogous to a series of bi-folding doors. The remaining portion of the envelope (the part further back from the nose) would consist of of fabric and ribs as found in our initial design.

Use of a Keel Structure to Enclose the Deflated Envelope

We are considering several means for protecting the envelope once it has been deflated. Straightforward approaches including covering the envelope materials with tarps and/or disassembling and folding up the craft for storage.

Another possibility is to incorporate a solid "keel" along the lower portion of the envelope. In this approach, the ship would more resemble a semi-rigid design. The keel could be constructed in such a way as to cover and protect the envelope material when deflated. Some design effort would be needed in order to ensure that portions of the envelope wouldn't fall clear of the keel during deflation and come to rest on the ground. Although such a design may need to sacrifice the convenience of ready disassembly, it would have the advantage of being a completely self-contained craft. It may be the case that eliminating the need for storage equipment at the landing site would be worth the a reduction in portability on the ground.

Choice and Combination of Lifting Gases

So far, we have limited our discussion to the use of hot air as a lifting gas. We think that hot air is an obvious choice for an initial basis of work. The reasons are many. Hot air is extremely inexpensive to generate. So inexpensive in fact that for recreational hot air balloons it is routinely disposed of after each flight. In addition, the technologies for creating, containing, and managing hot air lifting gas have undergone active development and refinement for nearly 50 years. These technologies are readily applicable to our work using off-the-shelf materials and tools. Likewise, the existing infrastructure for hot air balloon construction and maintenance is unmatched by any other choice of lifting gas. However, we do not expect to limit ourselves exclusively to the use hot air over time.

Use of Steam as a Lifting Gas

The most straightforward extension of our work will be to investigate water vapor (steam) as a lifting gas. Steam shares hot air's advantages of ease of generation and disposal.

Steam is an attractive choice of lifting gas because of its superior lifting ability. Steam can provide roughly twice as much lift as hot air for a given volume.* But at this point in time, the technologies for effectively generating and containing steam are not nearly as refined as for those for hot air. We eagerly await the developments of other investigators working with steam-based lift.

In addition to considering future designs using steam as the sole lifting gas, we see much promise in combining hot air lift with steam lift. Of particular interest are configurations that surround one or more internal cells of steam with hot air.

We see several advantages to this approach. For instance, one of the significant issues when using steam as a lifting gas is the fact that the gas is continuously condensing on the walls of the envelope. This condensation has two undesirable consequences. The first is the addition of parasitic weight as the newly condensed water drips down the inside of the envelope. The second is the need to incorporate a boiler large enough to continuously revaporize the condensing steam.

If however, one contains the steam inside cells that are surrounded by hot air that is kept above 100° C, then in-flight condensation is vastly reduced if not eliminated. If surrounded by sufficiently hot air, the steam will have no tendency to condense on the sides of the envelope. Buoyancy control could be obtained by varying the temperature inside the envelope. In order to avoid pressure fluctuations inside the steam cell, the volume of the steam cell could be allowed to expand and contract as necessary. Alternatively, one could vary buoyancy by keeping the temperature of the envelope essentially constant and changing the volume of steam in the inner cell via boiling and venting.

We believe that the ribbed envelope design described above provides a useful platform with which to experiment on steam/hot-air hybrid designs. Since the aerodynamic loads are carried exclusively by the outer envelope, the fabric forming the inner steam cell can be allowed to go slack as the steam contracts. Relieving the steam cell of aerodynamic loads may allow the fabric of the steam cell to be much lighter than would be possible otherwise as well as possibly providing a wider choice of fabrics. Further design latitude is provided by the fact that the inner steam cell can be maintained at a wide range of pressures.

Use of Helium as a Lifting Gas

We have not actively pursued designs using helium for a variety of reasons. One reason is that one of the primary advantages of a folding rib envelope is its ready inflation and deflation. Inflation and deflation are most practical when the lifting gas can be economically created and vented. Helium is too expensive to consider frequent disposal and is challenging to store.

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* See Goodey[4] for an extensive discussion of this point.

If the helium must be retained between flights when the envelope is deflated, then it needs to be stored at ambient pressure or recompressed. Clearly if the helium is removed from an airship at ambient pressure it needs to be stored in a tank that is as large as the volume of the airship. Having such a large tank negates many of the operational advantages of having a ship that is typically deflated when on the ground.

There may nonetheless be some advantages to a separate storage arrangement. For instance, the helium can be stored in an underground tank or in a set of small bladders that are easier to manage. Recompression of helium is extremely time and energy consuming as it requires expensive compressor equipment and high pressure storage tanks.

Use of a Ribbed Envelope for a Helium Ship

It should be noted however that a ribbed envelope may be worth considering for use on an otherwise conventional helium-based craft. There is no requirement that a ribbed envelope be deflated after each flight. Its structural efficiency alone may be sufficient to warrant its use.

The presence of the ribs would allow the use of little or no active pressurization of the helium in the envelope. As such the helium would be less prone to leakage. Further, the helium could allowed to expand and contract with changes in ambient temperature and pressure. The elimination of pressurization blowers as well as the potential use of lighter weight fabrics may conceivably compensate for the added weight and cost of the ribs.

Another option to consider is a Roziere design that uses a combination of helium and thermal lifting gas. For instance, one might enclose the helium in one or more internal cells or bladders. The sizing of the helium bladders in a Roziere design offers a wide range of potential configurations that trade off maximum lift and maximum buoyancy control. An interesting balance may be struck by sizing the helium volume so as to support the empty weight of the ship with the hot air portion supporting the useful load.

Advanced Maneuvering System

One of the most significant operational advantages of a hot air airship is its ability to hover safely at low altitudes without creating large amounts of downwash and/or noise. A critical performance criterion will be the amount of wind in which these aircraft can operate and still be able to remain relatively motionless. This will present an important avenue of future work.

We expect to take advantage of the two well supported points on the nose and tail of a ribbed envelope. These hard points are the most promising places for locating position control thrusting devices. The ribs that run longitudinally also provide useful attachment points. However, the load distribution provided by the individual ribs is not nearly as effective as that of the nose/tail attachment points.

We are also particularly interested in using electric motors for creating positioning thrust. Modern "brushless DC" electric motors provide the advantages of easy installation, reversibility, full torque throughout their range of RPM, and smooth operation in all orientations.

Electric motor based systems provide a great deal of design flexibility. In particular, power created by a centralized generator can be transmitted to different motors as needed during the various phases of flight. In that way, electric generation capacity does not need to be duplicated for each motor.

Another advantage of electric motor based systems is the opportunity to use battery packs or similar means to deliver large amounts of power for short periods. Using battery packs to handle demand peaks allows the use of a smaller electric generation systems.

When considering the propellers used to create positioning thrust, we see two interesting directions to pursue. The first approach is to use conventional propellers oriented perpendicularly to the longitudinal axis of the ship. The second option is to use cycloid propellers that can provide rapidly adjustable positioning thrust on two axes.

Co-generation of Heat for Lift as a Byproduct of Propulsion

One of the strongest objections to the use of heated lifting gases is the added fuel consumption needed to compensate for heat loss from the envelope. We point out however that a great deal of "waste" heat is produced by virtually every type of existing or proposed propulsion system. It seems reasonable to consider capturing all or some of this currently unused energy for the purpose of heating the lifting gas.

Little work has been done on the issue of lift co-generation in the past. One important reason for this lack of attention is that the primary airship technologies to date (internal combustion engines and pressurized envelopes) are a poor combination for co-generation. The waste heat from an internal combustion engine is most easily captured by capturing the engine exhaust gases. However, any attempt to duct engine exhaust gas into a pressurized envelope will necessary present a "back pressure" to the internal combustion engine. Back pressure typically reduces the effective operation of internal combustion engines. Our design is operated at ambient pressure which eliminates the problems presented by back pressure.

While it seems relatively straightforward to capture the exhaust gas from an internal combustion engine, even more promise is to be found in novel propulsion systems. There are in fact a plethora of such new propulsion system under development by other investigators.

Alternative Power Gerneration Technologies

So far we have described the use of a internal-combustion-engine/electric propulsion system. The choice of this initial configuration was made as a matter of expediency rather than a belief that is the best possible choice. In particular, our design strives for quiet operation and internal combustion engines are not know for being very quiet. Alternatives worthy of future consideration include fuel cells, steam engines and Stirling engines.

Fuel cells

Fuel cells are undergoing rapid and wide development as a means for providing electric power for land vehicles. We are hopeful that at least some of the systems currently under development will be applicable to our electric motor based propulsion and maneuvering systems.

It is important to note that there are multiple families of fuel cell technologies. Each of these technology families has different operating temperatures. Some, such as Proton Exchange Membrane systems, operate at less than 80°C. These systems may be suitable for producing electricity, but it is unlikely that they will be well suited for co-generation of heat for lift. In contrast, Solid Oxide Fuel Cells typical operate at temperatures between 500° and 1000° C providing greater opportunity to capture waste heat for lift.

Steam Engines

As described above, there are advantages to using steam as all or part of the lifting gas. As such, it may be worth pursuing configurations that use a steam engine as the boiler portion of a steam lift design.

Stirling Engines

The use of a Stirling heat engine to generate propulsion and maneuvering power also offers promise. In theory, a Stirling engine can operate on any temperate differential. However the greater the temperature differential, the more effective the engine. No matter what the range of temperatures used, a Stirling engine is typically described as having a "hot" portion and a the "cold" portion. Several Stirling based configuration are possible.

The "hot" portion of the engine can be placed at the point of fuel combustion or merely placed inside the envelope. Likewise, the "cold" portion of the engine may be located either outside the envelope or inside the envelope, away from the combustion. Configurations in which both ends of the engine are inside the envelope and take advantage of the naturally occurring internal temperature gradients are also possible.

Another point worth considering with regard to Stirling engines is size. Some of the more efficient Stirling designs are difficult to implement because they require that two large surfaces be exposed to the different temperature zones. More than on any other type of vehicle, a hot air airship already has unusually large surfaces with significant temperature differentials.

Solar Heating and Power

Like other investigators, we have considered the use of solar energy for electric power[5]. In addition, we will consider the possibility of using a passive solar mechanism to heat the lifting gas as is often done for demonstrations using "solar balloons."

The use of a folding rib envelope offers the advantage of eliminating the power drain of a pressure management system. This reduction in power requirements may prove very helpful to a solar airship.

However, the routine folding of the airship envelope will make selection and placement of solar cells difficult. Leaving the envelope inflated between flights eliminates many of the operation advantages of a envelope design.

Nonetheless, the possibility of a completely solar powered airship (for both heating and propulsion) is indeed intriguing.

FUTURE APPLICATIONS AND MARKETS

While our initial designs are targeted for application to the leisure market, we see several follow on applications. As with the wide variety of technical directions listed immediately above, the market directions listed below range from the straightforward to the extremely distant. Our intent is to provide the reader with food for thought rather than to describe our development intentions per se.

Construction Lift

The most immediate secondary application of our designs is to the heavy lift construction market. Buoyancy control and the possibility of well controlled hovering flight are particularly applicable to construction tasks. The ability to readily deflate and disassemble the airship for rapid transport between job sites is also a distinct operational advantage. Currently, heavy lift helicopters can not be used in many situations. Operating over areas sensitive to noise and/or downwash is a particular problem. Likewise, the presence of obstructions often makes the use of helicopters impractical.

Silent operation without downwash will allow safe and non-disruptive operation at low altitudes and relatively near obstructions. Clearly much work along the lines of the advanced maneuvering systems described above will need to take place before the construction market can be addressed seriously.

Advertising

Another close follow-on application is aerial advertising. Here the lower lift per unit volume provided by hot air is much less of an issue. Advertisers are more than willing to have a larger surface for displaying their message. It remains to be seen if the ground handling challenges presented by a larger envelope are worth the ready control of buoyancy and rapid inflation/deflation.

Another major operating limitation of the hot air airships built to date is their fairly low operating air speeds - 20 to 25 knots at the most. Higher operating speeds are required in order to adequately address the advertisers requirements for timely and predictable display of their message. We see much promise in this direction for our design approach. In particular, as described above, we should theoretically be able to double the airspeed of the ship while increasing the weight of the ribs supporting the envelope by a factor of only 1.6. However, in order to avoid excessive power requirements, we will most likely need to employ an envelope with a higher fineness ratio than our original design.

Sightseeing and Aerial Observation

Our current design direction also has advantages when considering sightseeing and aerial observation applications. A serene flight experience may prove to be an important factor in pleasing sightseers. For this application, the primary advantage of our design is reduced noise. The noise created by current pressurization and propulsion systems can do much to spoil the enjoyment of flight. Similarly, the quiet operation of an aerial observation platform would greatly enhance its effectiveness. A silently operating airship allows observation while itself being relative less noticeable. Likewise, a quiet airship will no doubt elicit fewer complaints from people on the ground. Although these applications may well benefit from some of the operational advantages provided by hot air lift and a ribbed envelope, we believe these will be secondary to the noise issues.

Large, Inseparable Loads

Further down the road is the application of our design approaches to the transportation of large inseparable loads. Some of the advantages of buoyancy control are immediately clear. Many previous designs have foundered on the need to rapidly take on ballast when delivering heavy cargoes. With a thermal airship this problem is essentially eliminated. Lifting gas can be rapidly vented or cooled in order to reduce lift.

Several hybrid aerodynamic/aerostatic designs have been proposed to avoid the need for ballast. We see thermal lift as offering significant advantages when incorporated into an aerodynamic hybrid craft.

Other investigators have proposed systems that use thermal lift for take off and landing and then supporting the weight of the aircraft aerodynamically[6]. These designs have used helium as the lifting medium. They incorporate a electrically driven heating element to heat the helium in order to obtain the increased lift for vertical take-off and landing. One could simply follow a similar approach using hot air or steam instead of heated helium. The lifting gas would be allowed to cool once the craft started to produce sufficient aerodynamic lift.

However, a ship that uses steam or heated air provides even more design options. One straightforward approach takes advantage of the relative ease with which the heat thrown off by the propulsion system can be captured. We envision a system where heaters are used to raise the temperature of the lifting gas during take-off and landing. Rather than allowing the lifting gas to cool completely during mid-portion of the fight, the "waste" heat from the propulsion system is used to create some additional aerostatic lift.

A Morphing Hybrid Design

An even bolder approach we have been exploring takes advantage of the relative ease and economy of producing steam and/or hot air. Under such an approach, the heated lifting gas is used support the entire craft during take off. Once the aircraft starts to accelerate and aerodynamic lift becomes available, the lifting gas can be deliberately released. With the release of lifting gas, the envelope can be folded or gathered while in flight.

Such a "morphing" aircraft design would have several advantages. Most importantly, the drag created by the large envelope volume could be vastly reduced. A morphing design would strive to alter the shape of the envelope while in flight into one that can efficiently create aerodynamic lift.

As the "morphing" aircraft approaches its destination, the envelope could be reinflate with lifting gas and the load once again supported aerostatically. Once landed, such a design could enjoy most, of not all, of the benefits of the thermal designs described above such as the ease of ground handling through buoyancy control and ready deflation. It may even be possible to strive for an envelope design that can be disassembled for transport back to the point of origin via land, sea or air cargo.

Clearly the production of morphing aerodynamic/aerostatic hybrid faces many unsolved research problems. Maintaining stability during the inflation and deflation stages may prove particularly vexing. In addition, developing an efficient structure that can change shape appropriately while still supporting the applied aerodynamic loads is a significant issue. However, it should be recalled that, difficult as a morphing structure may be to design, it is only worth considering for a hot air or steam based airship where lifting gas can be readily and economically created and vented.

CONCLUSION

To date, we have built numerous models with ribs that range for 3 meters in length to 10 meters in length. Initial results from models of our designs have encouraged continued development. We continue to field test the larger of these models to confirm their structural integrity under aerodynamic loads.

We expect to shift our focus in the very near future to the construction of a full sized, 2 person ship. We expect the volume of the envelope of this ship to be roughly 4,500 cubic meters with ribs that are 39 meters in length. The initial configuration of this ship will use conventional balloon heaters and internal combustion engine based propulsion. After flight testing of the initial configuration, we expect to supplement the propulsion system with hybrid electric propulsion and thrusting systems.

We find much promise both in our current designs as well as the steps that we believe will be followed once the current craft is in operation. We expect that the application of some of the novel designs described here will provide new approaches to some of the most significant obstacles limiting the use of aerostatics in the past.

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