52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference
4 - 7 April 2011, Denver, Colorado

AIAA 2011-1717

Airship Buoyancy Control Using Inflatable Vacuum Chambers

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Buoyancy control is identified as a significant problem in airships, past and present. An existing proposal to enhance the control of buoyancy in lighter-than-air aircraft is reviewed and a new method of buoyancy control (the inflatable vacuum chamber) is proposed. The differences between the existing proposal and new proposal are highlighted, including the new possibility of an airship that lands vertically onto the ground without a mooring mast, a ground handling party, or a runway. Theory of lightweight stiff inflatable structures is discussed and a specific design and construction method is proposed. The design is optimized and confirmed elastically stable; design specifications are given. A typical operation cycle (including liftoff, flight, and touchdown) is detailed. An area of potential theoretical advancement is identified.

I. Introduction

"Many of the airship's principal operational problems are associated with the functions of buoyancy control ..."[1] (Dr. Edwin Mowforth, vice president of the Airship Association, vice president of the Airship Heritage Trust). This fact is demonstrated in airship history. The USS Akron was lost when she was forced into the sea by a strong downdraft. The USS Macon was lost after her captain, in a panic over a potential loss of buoyancy, ordered a massive and irreversible discharge of ballast; the Macon rose above pressure height (the altitude at which her gas bags expand beyond the total volume of her airframe), lost lifting gas, and eventually crashed into the sea. The loss of the USS Shenandoah might have been caused by airframe damage resulting from a breach of pressure height. Of the US Navy's airships, only the USS Los Angeles met her end of old age, however, she too suffered from an inability to adjust her weight to meet changing conditions (see Figure 1).

In modern airships, the usual buoyancy control problem is that of compensating for the weight of fuel consumed in flight.[*] Inability to control buoyancy effectively also creates difficulty with landing, takeoff, and load exchange. Difficulties with weight of fuel consumed during flight can be handled in many ways. Fuels of various densities (gases and liquids) can be used (as in the LZ 127 Graf Zeppelin). Vectored thrust can compensate to an extent. Difficulties with landing and takeoff are often avoided completely by not landing but instead mooring some tens of feet above the ground. An airship that actually lands and takes-off can solve some of the buoyancy problem with aerodynamic lift, but this requires the airship to make a run along the ground (a runway) for take-off and landing and thus erodes the airship's prized "land anywhere" ability. Airships can also discharge ballast on liftoff, but discharge of lifting gas on touchdown is cost prohibitive. Load exchanges must be balanced, thus a load cannot be dropped except where sufficient ballast is available.

There are a variety of standing proposals to allow an airship to reversibly change its weight in flight. They include pressurization or heating of the entire gas contents of the airship, compressed storage of the lifting gas or air, and liquefaction of the lifting gas or air. A good review of these techniques can be found in Ref. 1. It is concluded that techniques involving pressurization or compression appear to be more practical than those involving heating or liquefaction.

The new Aeroscraft (Worldwide Aeros Corp.) is anticipated to use compressed air storage to control buoyancy reversibly. The Aeroscraft will be outfitted with high pressure tanks in which air can be pumped to gradually increase the weight of the ship. When the tanks are full, weight can be discharged rapidly by venting the tanks.

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[*] Personal correspondence with Edwin Mowforth, 14 August 2010.

This capability could assist with fuel weight compensation, vertical ground takeoff (instead of mooring), and rapid loading of cargo. But without a method of rapidly adding weight, the operations of vertical ground landing and rapid unloading of cargo remain difficult. These cannot be accomplished with a compressed air tank because air pumps are too slow or too heavy. It can be shown that if the pump is of equal weight as the storage container, it could take hours to fill the tank, yet only seconds to empty it. Thus rapidly and reversibly adding weight to an airship "in flight" can be accomplished only with a tank of negative pressure. Unfortunately, conventional vacuum chambers are impractical for this purpose because of their large mass (high weight). However, a recent development, the inflatable vacuum chamber,[2] allows for vacuum chambers of smaller mass (low weight) and thus it is now interesting to explore the potential application of vacuum to airship buoyancy control. The idea of using vacuum in an airship is not new. It dates back to 1670 when it was first proposed by Italian monk Francesco Lana de Terzi (see Figure 2).

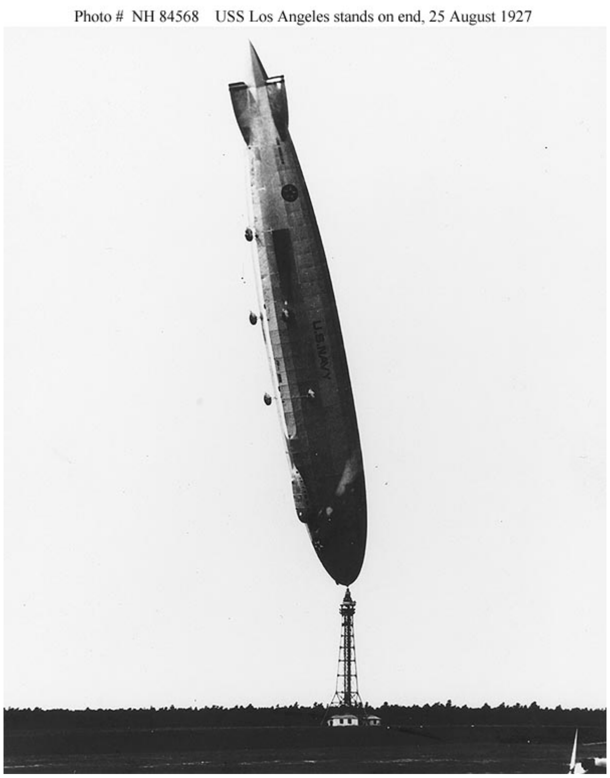

Figure 1. The U.S.S. Los Angeles after being struck by a tail wind while moored (1927)

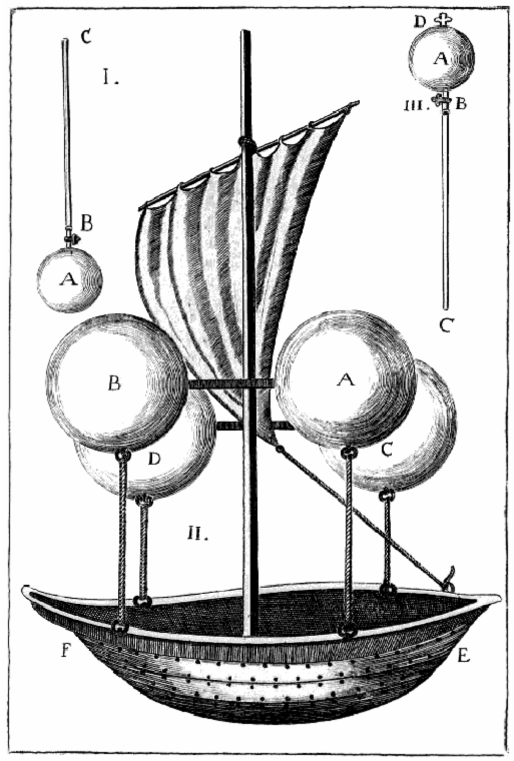

Figure 2. Francesco Lana de Terzi's flying boat concept c.1670

We now introduce this new possibility for buoyancy control, the inflatable vacuum chamber or IVC. Buoyancy control using an IVC is most closely related to the before mentioned techniques involving pressurization or compression. These techniques will be briefly reviewed first. The IVC will then be discussed.

II. Buoyancy Control Using Compressed Air Storage

First we explore the idea of storing compressed air on the airship. For such a system it is important to know the weight of the container and the weight of air it will be able to store. Often the limiting factor for a buoyancy control system is its weight. An ideal system would allow the airship to change its weight by a large amount quickly while adding only a small amount of weight to the airship itself.

We first propose that the air be stored in long cylinders of continuously wound fiberglass composite. In such cylinders, the glass fibers are wound at an angle of $54.7356° \approx \arctan\left(\sqrt{2}\right)$ to the axis of the cylinder to provide strength around the circumference that is twice the strength along the axis. (When a cylinder is subject to hydrostatic loading, the stresses in the circumference are twice those along the axis.) It can then be shown that the total weight of the container (excluding end effects) is

$$m_{\text{tank}} = m_{\text{air-stored}} \frac{3P_{\text{air}}}{\rho_{\text{air}}} \left(\frac{\sigma_{\text{composite}}}{\rho_{\text{composite}}} \right)^{-1} \quad (1)$$

where the m's are masses, P is pressure, the ρ's are mass densities, and $\sigma_{\text{composite}}$ is the strength of a unidirectional sample of the composite material on its strong axis. Note that $P_{\text{air}}/\rho_{\text{air}}$ depends only on the temperature and not on the storage pressure (ideal gas law). It is also true (and more difficult to show) that (1) is also valid for containers of arbitrary shapes including cylinders with hemispherical ends, spheres, and ellipsoids as long as the material comprising the structure of the container is in tension only (no compressive forces). (For a proof of the previous statement, see the Appendix.) Because (1) is applicable to general shapes, it is also valid for pressurizing the entire volume of lifting gas in the airship. In that case, however, one considers the stress to density ratio of the fabric (not composite) that carries the pressure load in the surface of the airship. (Reference 1, pp. 360-363 appears to contradict the idea that Eq. (1) is valid for pressurizing the entire envelope of the airship. The author of Ref. 1, however, acknowledges in private correspondence with the present author[†] that the choice "$k_s = 10$" on Ref. 1, p. 362 does not follow from any known discussion and is likely in error. It is the belief of the present author that Eq. (1) is applicable to any pressure container, including the entire envelope of a non-rigid airship.)

For air at 15° C, $P_{\text{air}}/\rho_{\text{air}} \approx 0.083\,\text{km}^2/\text{s}^2$. For a 60/40 composite of E-glass/epoxy loaded at a safety factor of 2, $\sigma_{\text{composite}}/\rho_{\text{composite}} \approx 0.500\,\text{km}^2/\text{s}^2$. Thus the mass of the tank will be approximately half the mass of the air the tank can store. If one substitutes a 70/30 composite of aramid/light-weight-epoxy loaded at a safety factor of 1.5, we find $\sigma_{\text{composite}}/\rho_{\text{composite}} \approx 1.25\,\text{km}^2/\text{s}^2$ and thus the mass of the container would be about one fifth the mass of air stored. It appears that containers of wound carbon fiber might have a mass six or seven times smaller than the mass of air they can contain.

Energy consumption of the required air pumps will likely not exceed 3% of the airship's total energy budget.[1] A survey of air compressor pumps (and vacuum pumps) on the market today indicates that they can easily pump a weight of air equal to their own weight in about 45 minutes. If engineered for minimal weight (for airship application) this could likely be improved by a factor of two.

III. The Inflatable-Vacuum-Chamber Concept

We now shift our attention to the potentially complementary system, the inflatable vacuum chamber. We can begin to understand the mechanics of the IVC by considering the following idealized structure. One imagines that there is a dense three-dimensional isotropic network of thin tensile fibers. These fibers are placed randomly and densely having all possible orientations and approaching a continuum. These fibers can be imagined to be glass, aramid, carbon, or otherwise. One then imagines removing regions of the tensile fibers to leave behind structures of a desired shape. For example, one might imagine leaving behind a spherical container consisting of the fiber segments in a volume between two concentric spheres of different radii, all other volumes void of fibers. One then imagines placing gas impermeable barriers along every surface where the volume of removed fibers meets the volume of remaining fibers. For the example of the spherical container before mentioned, this would consist of two spherical membranes coincident with the before mentioned spherical surfaces. Because the fibers carry only tension and not compression, the space between the fibers must be pressurized to provide the idealized solid with the ability to transmit compressive forces. One thus imagines that the severed ends of the fibers are mechanically connected to the membrane such that the space occupied by the fibers can be pressurized and the resulting tensions in the fibers will be terminated in the membrane (see Figure 3). The distance between the fibers is considered to be small compared to the thickness of the membrane such that the stresses in the membrane can be neglected. Note that the membrane does not carry any of the stresses resulting from pressurization. The force imparted to the membrane by fiber attachments is balanced by the pressure force.

A structure such as this is filled mostly with gas and thus has a low density. Pressure and fiber cross-sectional area can be reduced proportionally to reduce the effective strength of the structure. This reduction however does not affect the effective strength to stiffness ratio of the idealized continuous solid or structure which it forms. This is in contrast to traditional compressive structures which, when designed for lighter loads, lose stiffness at a proportion much greater than the proportion by which they lose strength. Corrugations and complex networks of compressive

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[†] Personal Correspondence with Edwin Mowforth, 13 March 2011.

members are often used to address this problem, but as the design load further lightens, it becomes nearly impossible to maintain the ratio of stiffness to strength, hence the difficulty in designing lightweight vacuum containers as compressive structures. This is the motivation for the idealized "inflatable solid" just described. Its design load can be reduced arbitrarily while maintaining its strength to stiffness ratio. Thus it can then be shown that, if this idealized spherical shell is sufficiently thick, the linear mass density of the fibers is sufficiently small, and the space between the fibers is sufficiently pressurized, the structure remains elastically stable when vacuum is introduced into the central space. Let us further consider this pressurized network of fibers.

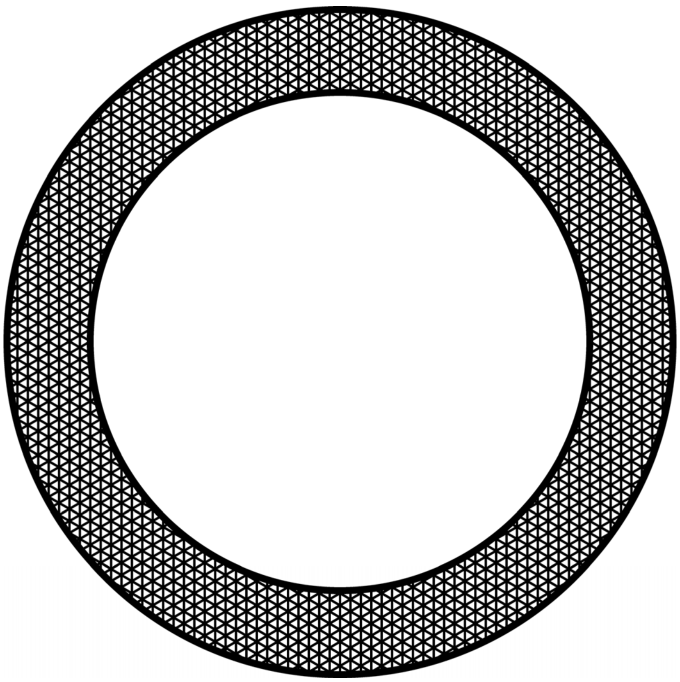

Figure 3. A cross-sectional view of the idealized spherical IVC. The thin lines represent tensile fibers; the thick lines represent gas impermeable membranes

In the idealized case, a pressurized matrix of tension fibers can be described mechanically as a continuous solid having a specified strength and elasticity. We will here show that, if the tension fibers are isotropic, the idealized bulk solid has isotropic elasticity and a Poisson's ratio of one-fourth. We will also show that the elastic modulus per mass and single-axis strength per mass of this idealized continuous material is one-sixth that of the fiber material.

We imagine a dense isotropic network of thin elastic tensile fibers having all possible orientations

$$a = \begin{bmatrix} \cos\theta \\ \sin\theta\cos\phi \\ \sin\theta\sin\phi \end{bmatrix} \quad \text{for all } \theta \text{ and } \phi . \tag{2}$$

We then imagine stretching the network of fibers on three principal axes of strain resulting in new orientations

$$b = \begin{bmatrix} 1+\varepsilon_x & 0 & 0 \\ 0 & 1+\varepsilon_y & 0 \\ 0 & 0 & 1+\varepsilon_z \end{bmatrix} a \tag{3}$$

where the ε 's are the strains. These new orientations have elastic energy per unit volume of fiber material equal to

$$u = \tfrac{1}{2} E \left(|b| - 1 \right)^2 \tag{4}$$

where E is the elastic modulus of the fiber material. To second order in the ε's, this is found to be

$$u \approx \tfrac{1}{2} E \left(\varepsilon_x \cos^2\theta + \varepsilon_y \sin^2\theta \cos^2\phi + \varepsilon_z \sin^2\theta \sin^2\phi \right)^2 . \tag{5}$$

We average this for all orientations of the fibers to find the average elastic energy per unit volume of fiber material,

$$\bar{u} = \frac{1}{4\pi} \int_0^{\pi} \int_{-\pi}^{\pi} u \sin\theta \; d\phi \; d\theta \approx E \left(\frac{\varepsilon_x^{\;2}}{10} + \frac{\varepsilon_x \varepsilon_y}{15} + \frac{\varepsilon_y^{\;2}}{10} + \frac{\varepsilon_y \varepsilon_z}{15} + \frac{\varepsilon_z^{\;2}}{10} + \frac{\varepsilon_z \varepsilon_x}{15} \right). \tag{6}$$

We identify this as the elastic energy of an isotropic elastic solid with an elastic modulus of $E/6$ times the fiber volume fraction and Poisson's ratio of 1/4. This consideration is valid only if the strain on all three principal axes is positive. Under negative strain, some fibers relax to zero tension and the analysis become non-linear.

Notice that with such a network of fibers it is not possible to have zero tension along any single axis without having zero tension along all axes. This is because only a very small number of fibers carry tension along a specific axis or in specific planes and none of the fibers carry compressive force. This means that such a tensile network always has a "background" tension, the transmission of which requires extra weight and extra pressurization to create force balance. For an example, consider the hydrostatically compressed spherical shell. The ratios of the tensions on the principal stress axes in the shell are 0:1:1 (radial : circumferential : circumferential). The idea of the pressurized tension network is to use pressures to achieve the isotropic positive part 1:1:1 and then use the tensile network to provide the additional reduction -1:0:0 needed to bring the total to 0:1:1. However the requirement of only positive strain requires a "background tension" of 1/2 and thus we must substitute -1:0:0 with -3/2:-1/2:-1/2. Thus pressure (and the initial loading of all fibers) has to be increased by 50% to provide the "background tension" to prevent negative strain on loading.

These difficulties can be reduced however if the fibers are not placed isotropically, but instead are placed primarily along the anticipated axes of principal strain when loaded. Unfortunately, this approach increases difficulties with elastic stability and the analysis thereof. Because stress in the idealized solid will be isotropic when the IVC is vented and will be primarily in the radial direction when vacuum is present, we find that practical IVCs have a large population of tensile fiber in the "almost" radial direction. This "almost" is necessary to mitigate issues of elastic stability. The structure of Figure 7a in Ref. 2 illustrates this philosophy of "almost" radial. In this example, the tensile fibers are part of a textile membrane. This is the structure that we propose for use in buoyancy control. Though spherical IVC's have better theoretical properties, we avoid them for difficulties in automating their construction and difficulties in producing double-curved (spherically curved) fabric membranes.

IV. The Proposed Structure

The structure has a cross-section shown in Figure 4 and is invariant in its length. Its inner radius is about 1 meter and its total length (continuous or non-continuous) is approximately 600 meters. It provides about 2 tons of buoyancy control range. The ends are closed crudely, by wetting the fabrics near the end of the structure with a sealant, placing a constricting band around the structure at that point, and then tightening the band until gas leakage is minimized. Ports and ducting are added to facilitate inflation and deflation.

It should be noted that buoyancy control systems that occupy large volumes create different amounts of buoyancy at different altitudes even if their gas contents do not change. For example, since the proposed vacuum volume displaces about 2 tons of air at sea-level and does not change its volume at altitude, its buoyancy is reduced by 0.62 tons at an altitude of 10,000 feet.

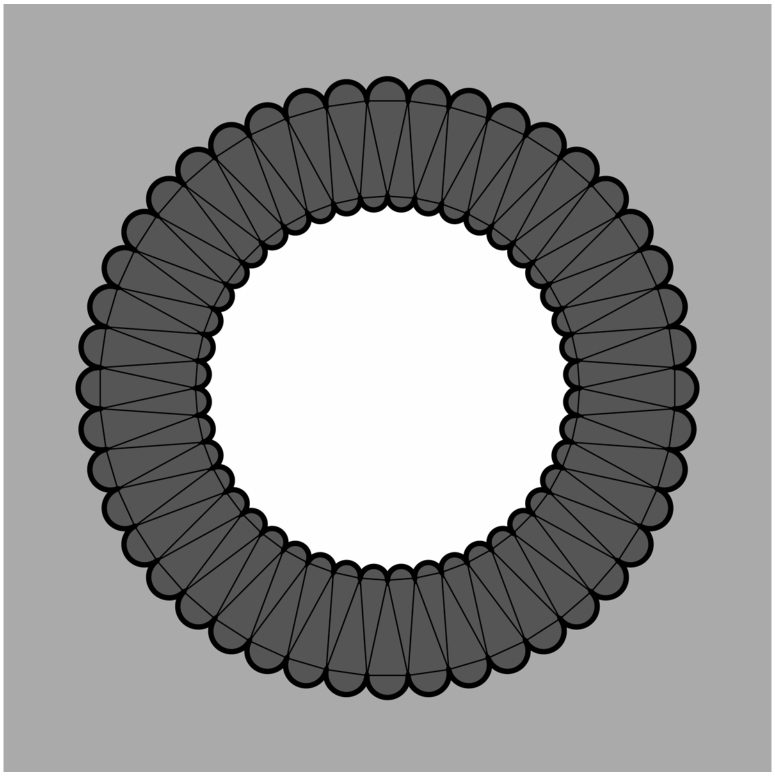

Figure 4. Cross section of the proposed structure (Lightly shaded exterior region represents low-pressure helium; heavily shaded regions represent high-pressure helium; unshaded interior region represents vacuum; thick lines represent gas-impermeable fabric; thin lines represent gas-permeable fabric)

V. Construction of the Proposed Structure

The proposed structure is formed of five layers of fabric. The innermost and outermost fabric layers (layers 1 and 5 respectively) are gas impermeable, i.e. the fabric has been impregnated with some gas impermeable resin. These five fabrics are sewn together with a lock-stitch sewing machine as shown in Figure 5. The structure is closed by sewing each of the five layers back to itself. The structure is preliminarily inflated at low pressure to give it shape. Lines of sealant are then placed between the lobes on the sewn seams to slow the gas leakage passing through the holes created by the sewing needle.

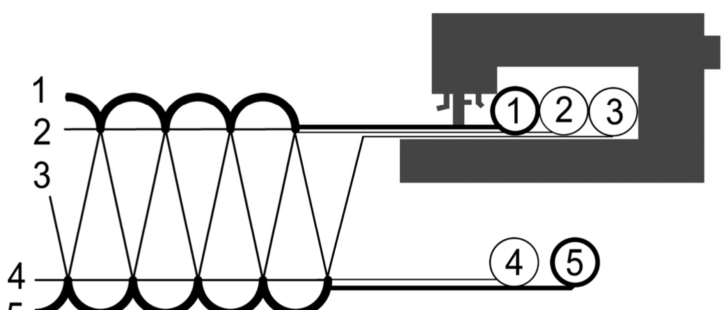

Figure 5. Method of constructing the proposed structure

VI. Stability of the Proposed Structure

The stability of the proposed structure is analyzed with techniques similar to those found in Ref. 2 with the following exceptions. The "effective tension" concept is not used. The angles of arc in the outer and inner lobes are added as additional degrees of freedom bringing the total number of degrees of freedom per unit cell from four up to six. The design strength of each membrane is calculated from the tensions present in the absence of vacuum. These tensions do not have a unique solution until one imposes the additional constraint that the tensions in layer 2 and layer 4 must be equal. This constraint is arbitrary. It may be found that releasing this constraint will allow the optimized mass of the structure to be slightly lower and thus further investigation is required. The elasticity of each membrane is set by assuming that the elastic modulus divided by the tensile strength is 34 (characteristic of aramid fiber fabrics[3]). The outside radius, number of lobes, and pressure are then varied keeping the inside radius fixed to find the structure with the smallest total membrane mass per unit volume of vacuum that has both elastic stability and positive tension in all membranes. As shown in the Appendix, the mass of gas the structure contains when vacuum is not present is directly proportional to the total membrane mass. Thus the weight of the pressurizing gas is not considered when optimizing the structure. The optimized structure is found to have an outside radius that is 1.50 times its inner radius, 44 lobes, and a pressure of 3.08 absolute atmospheres in its wall. The failure mode of the structure is shown in Figure 6.

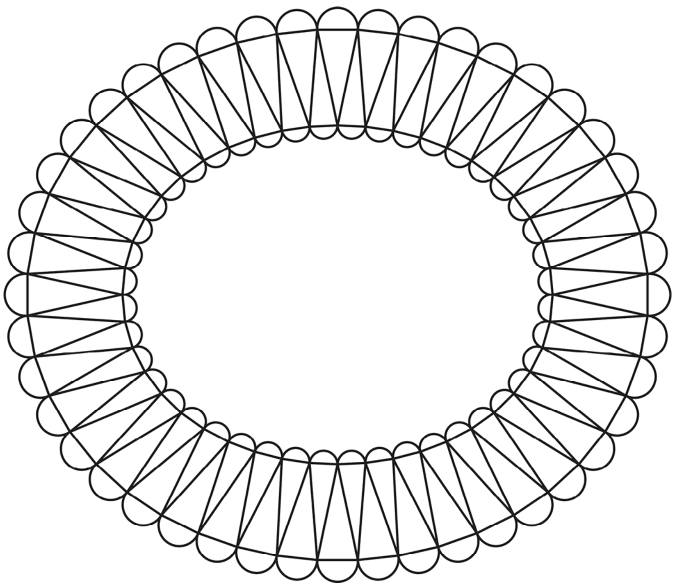

Figure 6. Failure mode of the proposed structure

VII. Specific Design

Table 1. General Specifications for the inflatable vacuum chamber

Design Specifications	
General Specifications	
Radius to inside sewn seam	1.00 meter
Radius to outside sewn seam	1.50 meter
Number of lobes	44
Absolute pressure in wall	3.079 atmospheres
Absolute pressure in central space	as low as 0.00 atmospheres
Safety factor	2
Total non-continuous length	581.1 meters
Volume of central space	1632 m^3
Pressurized volume	2965 m^3
Total volume	4597 m^3
Fabric of epoxy-impregnated aramid fibers:	
Density of fibers	1.44 g/cm^3
Strength of fibers	3.6 GPa
Elastic modulus of fibers	124 GPa
Total fabric weight	1499 kg
Total weight of axial fibers	499 kg = 1/3 total
Total weight of perpendicular fibers	1000 kg = 2/3 total
Fabric Densities:	

Layer 1	18.080 g/m^2 (not including gas-impermeable resin)
Layer 2	61.339 g/m^2
Layer 3	22.972 g/m^2
Layer 4	61.339 g/m^2
Layer 5	27.120 g/m^2 (not including gas-impermeable resin)

Table 2. Weight components of an operational inflatable vacuum chamber

Weight Components	
Fabric weight	1.499 ton
Extra helium required to pressurized	1.042 ton
Helium removed when evacuated	0.276 ton
Total weight added to airship when fully charged	2.265 ton
Weight of air displaced when central space is evacuated	2000 kg
Weight of air un-displaced when central space is vented	2000 kg
Weight of air displaced when wall is vented	7552 kg
Weight of air immediately displaced when wall is vented	4478 kg

Table 3. Buoyancy control capabilities of the inflatable vacuum chamber

Buoyancy Control Capabilities
At Sea-Level When Fully-Charged (both vacuum and pressure)
• Can gain 2.00 tons of weight and immediately after can lose 4.478 tons of weight. As adiabatic cooling dissipates, an additional 3.074 tons are lost. Results in total discharge.
-OR-
• Can lose 2.478 tons directly. Again, an additional 3.074 tons are lost as cooling dissipates. Results in total discharge.
At Sea-Level as a Pressure Vessel (when pressure is charged but vacuum is not)
• Can lose 4.478 tons of weight. As adiabatic cooling dissipates, an additional 3.074 tons are lost. Results in total discharge.

VIII. System Operation

The "2-ton" system proposed here (schematically shown in Figure 7) is designed to aid with vertical take off (or liftoff), weight compensation for fuel consumed during flight, and vertical landing (or touchdown). Larger systems would be required to adjust buoyancy for on loading and off loading of cargo.

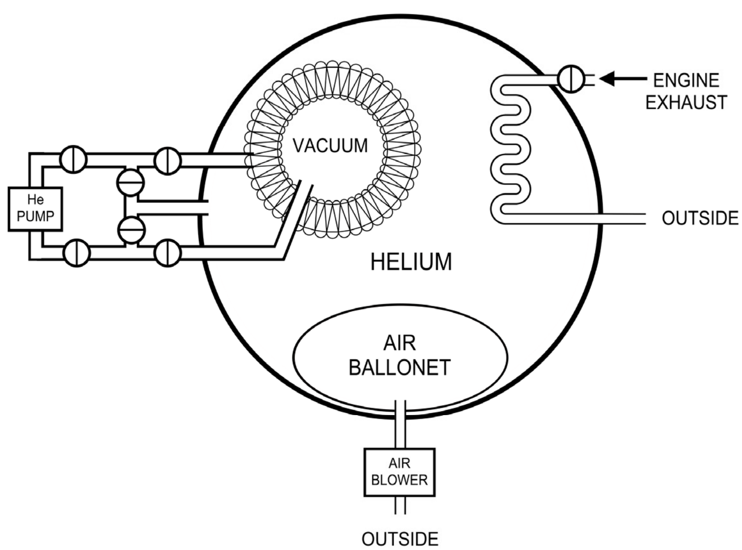

Figure 7. Schematic representation of the IVC buoyancy control system

The IVC functions as both a vacuum chamber and a pressure vessel. Its weight efficiency as a pressure vessel is equal to that of pressure vessels of simpler designs (see Appendix). It however has the additional ability to contain vacuum (in addition to pressure) when sufficient pressure is present. An IVC buoyancy control system thus has the same weight and buoyancy control range as a system that only compresses gases, but has the additional benefit of being able to rapidly add weight. This comes at the cost of having a storage vessel of more complex geometry.

We consider here an airship displacing approximately 100 metric tons of air at sea level having a fuel capacity of about 5 (metric) tons. It experiences a drag force of about 2 metric tons (metric ton force) at its top speed of about 100 km per hour. It is equipped with a 2000 horsepower engine and has a range of 1000 km. It flies at altitudes up to 10,000 feet.

We begin with the airship on the ground, at sea-level, no vacuum in the center of the IVC, full pressure (about 30.6 psi gauge) in the wall of the IVC, and no fuel. In this condition, the airship has been designed to have a net buoyancy of -2.00 tons, giving it traction with the ground. It is not moored. In preparation for liftoff, 5.55 tons of fuel are added. The net buoyancy is now -7.55 tons.

As time for liftoff approaches, engines are started and engine exhaust is directed through the heat exchangers warming the helium contents of the airship to produce 5.55 tons of superheat buoyancy. While it appears that this is feasible to do for a short period of time,[1] more investigation is needed to confirm this. The net buoyancy is now -2.00 tons.

When the ship is prepared for liftoff, the wall of the IVC is vented releasing compressed helium into the envelope of the ship. The helium cools adiabatically as it expands and buoyancy surges by 4.48 tons. Net buoyancy is now +2.48 tons. In absence of vertical winds or assistance from vectored thrust, this produces about 1/40 of a "g" of vertical acceleration.

Immediately after liftoff, the heat exchangers are closed and thus heating of the lifting gas is discontinued. The airship's lifting gas now contains a pocket of "hot" helium (resulting from the lifting-gas heating) and a pocket of "cold" helium (resulting from the adiabatic expansion of the helium released from the IVC). As these temperature variations dissipate to the atmosphere, 2.48 tons of buoyancy are lost bringing the net buoyancy to 0.00 tons. The IVC system is now fully discharged. Simultaneously, as the airship climbs to 10,000 feet, the valves venting the interior and wall of the IVC remain open allowing the reduction in ambient pressure to further evacuate all parts of the IVC, thus buoyancy remains balanced.

Once an altitude of 10,000 feet is reached, valves to the IVC are shut, "locking-in" the density of the IVC system. Because of the fixed volume of the IVC, the airship will tend to stay at 10,000 feet. A variation of 1,000 feet in altitude will create a change in buoyancy of about 0.13 tons that will tend to return the airship to 10,000 feet. This oscillation of the airship's altitude will have an approximate period of 17 minutes.

For the next 10 hours or so, the airship flies its course of approximately 1000 km during which in consumes almost all of the 5.55 tons of fuel added. Simultaneously, a helium pump (thought to weigh about half a ton) removes helium from the interior of the IVC and from the envelope of the airship and forces it into the wall of the IVC to create a near vacuum in the interior of the IVC and a pressure of close to 28.0 psi gauge in its wall. This net compacting of the helium results in a reduction of buoyancy of close to 5.55 tons, precisely balancing the weight of lost fuel. The net buoyancy remains at 0.00 tons and the fuel tank is close to empty.

As the helium pump continues to increase the gauge pressure in the wall of the IVC beyond "close to" 28.0 psi (where "close to" corresponds to the small weight of fuel remaining), the altitude for aerostatic equilibrium (which was 10,000 feet) begins to decrease, and the airship begins to descend. As the density and pressure of the ambient atmosphere increases, the buoyancy of the IVC system begins to rise and (in absence of continued pumping) the gauge pressure in the wall of the IVC would begin to drop. Thus pumping continues to surpass changes in ambient pressure and bring the gauge pressure in the wall of the IVC to "close to" 30.6 psi as the airship approaches the ground. Net buoyancy remains at 0.00 tons.

As touchdown approaches, the pilot prepares to vent the vacuum in the central space of the IVC. When first contact with the ground is made, the IVC is vented rapidly decreasing the net buoyancy by 2.00 tons. Net buoyancy is now -2.00 tons and thus traction with the ground is secured. For rapid return to the air, refueling and superheating of the lifting gas occur simultaneously.

Note that in this proposed system, the IVC vacuum space is vented with helium and not air. Note that the buoyancy change for the ship is the same in either case. In both cases, some gas already in the ship is moved into the IVC to make room for more air to flow into the air ballonet. The addition of new air to the air ballonet is what actually changes the weight of the ship. Additionally, moving helium instead of air into the IVC has the advantage of reducing the pressure height of the ship whenever vacuum is vented. This might be useful in the event that the

IVC system is used in flight for disaster avoidance. A similar argument shows the advantage of pressurizing the wall of the IVC with helium. Furthermore it is useful for the central space of the IVC and the wall of the IVC to contain the same gas so that only one pump is required to manipulate the gas.

IX. Future Theoretical Work

When pressure in the wall of an IVC containing vacuum is sufficiently reduced, instability will occur. This instability may potentially collapse a large fraction of the volume occupied by the vacuum. It might also be true that, immediately after the collapse, slightly increasing the pressure in the wall might restore the volume of vacuum. If such a "tipping point" phenomenon occurs, it might be useful in airship design. If one can manipulate such a tipping point with only small changes in pressure, one might move large volumes of gas with only small amounts of pumping. This may lead to a buoyancy control system that does not need charging, one that can switch back and forth from its heavy state to its light state at will by simply collapsing and un-collapsing its IVC at this tipping point of stability/instability.

Appendix

We here prove that Equation (1) is applicable to arbitrary shapes. We consider a number of tensile fibers bonded together with a resin to form tensile shells (or membranes). These tensile shells form structures which contain pressurized gas. We assume that fibers are only placed where needed for strength and thus all fibers are at their maximum working load when the pressure is introduced. We first integrate the trace of the stress tensor σ_{ij} over a volume that contains the entire structure (including all fibers, resin, and pressurized gas). We everywhere offset the stress tensor by the ambient pressure such that the pressures considered are gauge pressures and the stress tensor outside the structure is zero.

$$\int_{\substack{\text{all}\\ \text{volume}}} \mathrm{tr}\left(\sigma_{ij}\right) dV = \mathrm{tr}\begin{bmatrix} P_{\text{gas}} & 0 & 0 \\ 0 & P_{\text{gas}} & 0 \\ 0 & 0 & P_{\text{gas}} \end{bmatrix} V_{\text{gas}} + \int_{\substack{\text{composite}\\ \text{volume}}} \mathrm{tr}\begin{bmatrix} -\sigma_{\substack{\text{composite}\\ \text{working load}}} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} dV = 3P_{\text{gas}}V_{\text{gas}} - \sigma_{\substack{\text{composite}\\ \text{working load}}} V_{\text{composite}} \quad (7)$$

Note that the tension in the composite is shown to occur only in the *x*-direction. This is clearly not true but also does not affect the result because the trace is invariant under rotations of the coordinate system.

Because the stress tensor at the boundary of the volume is everywhere zero and because the divergence of the stress tensor is zero (momentum conservation), it is true that $\int_{\text{all volume}} \sigma_{ij}\ dV = 0_{ij}$. And because the trace of the integral is the integral of the trace, it is also true that

$$\int_{\text{all volume}} \mathrm{tr}\left(\sigma_{ij}\right) dV = \mathrm{tr}\left(\int_{\text{all volume}} \sigma_{ij}\ dV\right) = \mathrm{tr}\left(0_{ij}\right) = 0 \quad (8)$$

and thus from (7)

$$V_{\text{composite}} = \frac{3P_{\text{gas}}V_{\text{gas}}}{\sigma_{\substack{\text{composite}\\ \text{working load}}}} \quad \text{thus} \quad m_{\text{composite}} = m_{\text{gas}} \frac{3P_{\text{gas}}}{\rho_{\text{gas}}} \frac{\rho_{\text{composite}}}{\sigma_{\substack{\text{composite}\\ \text{working load}}}} \quad (9)$$

which is (1).

Acknowledgements

The author would like to acknowledge Jack Sams for bringing together the right people to generate this idea, Ian Winger for developing techniques for constructing inflatable structure from fabrics, Helena Safron for editing this document, Edwin Mowforth for sharing his lifetime of experience with lighter-than-air aircraft, and Frank Flaherty for useful discussion.

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