AC 2011-957: NOVEL AERONAUTICAL ENGINEERING STUDENT PROJECT: DEVELOPING ULTRA-LIGHT-WEIGHT AERIAL VEHICLE DESIGN AND PROOF OF CONCEPT

Horacio Andrs Trucco

Mr. Trucco was a Vice President and Principal Scientist at GASL, Inc., where he has been a full-time staff member since 1968 until 1994. He headed both the design and fabrication departments. His activities have involved projects related to analytical and experimental research in advanced propulsion systems and components, low and high speed combustion, air pollution and energy conservation. Mr. Trucco was responsible for design and fabrication of wind tunnel components such as air heaters, water-cooled nozzles, vacuum-producing air ejectors and scramjet engine models for both the NASA Langley Research Center and NASP related programs. In particular, Mr. Trucco has been involved in planning and designing a low speed premixed combustion test apparatus for NASA Lewis and premixed and diffusion type supersonic combustion tests for NASA Langley, the design and manufacture of a laser diffuser model for NASA Ames and an x-ray scanner for computerized tomography for an industrial client, the design of a transonic wind tunnel for NASA Langley and the development of industrial burner concepts to improve combustion efficiency and reduce emission levels. He has also been responsible for an analytical study of bypass turbojet engines with supersonic fans for NASA Lewis, for design of a turbofan engine simulator for wind tunnel testing for General Dynamics, for the analysis of an advanced helicopter propulsion concept for the Allison Division of General Motors, and for an experimental research in coal-water slurry fueled diesel engine. Prior to 1968, Mr. Trucco was employed as Research Scientist by The Marquardt Corporation (1966-67) where he was responsible for operation of their Hypersonic Hot-Shot Tunnel. From 1965 to 1966, he was employed by the Argentine Air Force as a scientist; he studied servo-controlled stagnation temperature probes that eliminate radiation error. From 1963 to 1965, he was employed by GASL where he participated in experimental hypersonic wake research, shock tunnel testing, engine performance prediction and scramjet inlet design. From 1955 to 1963, he was employed by the Argentine Air Force Aeronautical Institute and was initially responsible for research and testing on reciprocating aviation and automobile engines and later for operation of a subsonic and a supersonic wind tunnel. During the period of 1957 to 1963, Mr. Trucco supported a concurrent university teaching activity in thermodynamics, mechanisms and propulsion. Mr. Trucco holds an Aeronautical Engineering degree (1955) and a Mechanical Engineering degree (1960), both from the National University of Cordoba, Argentina, and a M.S. Astronautics degree (1965) from Polytechnic Institute of Brooklyn, New York (currently known as Polytechnic University).

Martina Y. Trucco, HP Labs

Martina Y. Trucco is responsible for research strategy and portfolio management at HP Labs, HP's global corporate research lab. Previously, she worked in HP Labs' Open Innovation Office and University Relations office, leading development of strategic university, commercial and government collaboration activities in the Latin America region, as well as global creative and marketing activities for the team. She is passionate about education and technology, and a believer in the power of partnerships between industry, academia and government to effect change in education and foster economic development.

Martina joined HP in 2004, after receiving her Master's degree with honors in Digital Business Management from HEC Paris and Tlcom Paris. She also holds a Bachelor of Science in Economics with a concentration in Multinational Management from The Wharton School of Business, at the University of Pennsylvania. Prior to joining HP, Martina worked in the e-business departments of Eli Lilly France and Louis Vuitton. She was a founding member of a start-up in Munich, Germany in 2000, specializing in Tablet PCs and mobile computing solutions and consulting. She is a member of the Board of Directors of ISTEC, the Ibero-American Science and Technology Education Consortium, and serves as Chair of the Advisory Board of the Caribbean Computing Center for Excellence.

NOVEL AERONAUTICAL ENGINEERING STUDENT PROJECT: DEVELOPING ULTRA-LIGHT-WEIGHT AERIAL VEHICLE DESIGN, FABRICATION AND HUMAN-POWERED FLIGHT TRIAL

Abstract

For students studying aeronautical engineering, one of the most exciting and motivating components of their curriculum is often their experience with novel aeronautical engineering student projects. In this paper, a novel inflatable structure concept is suggested for the design and manufacture of ultra-light-weight aerial vehicles, for example personal glider planes, human-powered planes, UAVs and outer-space devices.

This paper will present a brief description of the novel design summarized below, and will also present alternatives for integration into various levels of aeronautical engineering curricula. The author is keen on providing support for one or several engineering programs to incorporate the novel student project, where there is interest and support from the faculty and institution. Interested programs would have the opportunity to pioneer design and testing of the novel concept with their students.

The proposed structure is fully collapsible when deflated permitting simple storage and easy transportation. Unlike previously known pressurized aeronautical structures, the concept yields flush aerodynamic surfaces similar to those obtainable by rigid structures, therefore assuring undisturbed air flow. Wings can be constructed with twist and dihedral geometry. In addition, the structure is capable of morphing during flight, permitting variation of its airfoil camber to optimized vehicle performance according to needs. The structure consists of three basic components, i.e., spar, rib and outer skin each inflated a different pressure. All components are formed from flexible thin lamina. The spars are tapered cylinders preferably reinforced with fibers. Ribs exactly reproduce wings and fuselage contour at its particular station. The outer skin rests on the rib's perimeter. The structure exhibits very high strength-weight ratio so as to allow the design of a 15 meter wing span human-powered plane weighting about 10 kilogram. A pilot could effortlessly carry such ultra-light-weight plane over his or her shoulders while running for safe takeoff or controlled landing. Such truly unassisted and controllable human-powered flight would symbolize achieving the long sought-after dream of flying almost like birds.

Overview of the Proposed Structure

A novel implementation of the inflatable structure (or pressurized structure) concept to build ultra-light-weight aerial vehicles specifically designed for human-powered flight is proposed. The main objective is: (1) to dramatically reduce the total weight and cost of manufacture of such an ultra-light-weight aircraft in comparison to the use of conventional rigid structures; (2) to permit safe takeoff and landing without on-board or external power assistance or on-land personnel help; (3) to offer the possibility of gradually varying the wing geometry in-flight to optimize aerodynamic performance according to flight conditions; and (4) to simplify storage and transportation of the aircraft after deflation.

It has been widely demonstrated that inflatable aircraft are resistant to violent impact because they do not break or permanently deform. They survive accidents where rigid structure aircrafts fail to survive. Accordingly, the proposed concept could also reduce the injury risk of the pilot involved in an accident. This concept was originally presented in an abbreviated form on February 7 and April 21 2007, see reference [1].

After a concise description of previous types if inflatable structure aerial vehicles, the novel concept is presented, and two kinds of ultra-light-weight aerial vehicles are suggested. Finally, a plan to integrate the idea into aeronautical student curricula is proposed for faculty.

Historical Background

Records of inflatable structures date back to antiquity; a popular contemporary application is the motor vehicle tire. Other useful applications include; ramps for emergency exit from airplanes, the automotive air bag, inflatable kites for surfing, inflatable parachutes, satellite and interplanetary inflatable devices and special components for military applications.

Between the years 1955 and 1962, the Goodyear Aircraft Company designed and built 12 inflatable aircraft for military rescue missions: the Inflatoplanes model GA-468 (a 40 HP single-seater) and GA-466 (a 60 HP two-seater), see references [2] and [3]. The ILC Dover Company built the Apteron, a radio-controlled inflatable flying-wing, see reference [4]. There are several examples of inflatable sports aircraft. The most simple and popular concept is the paraglider that self-inflates by ram-air pressure. Small UAV (Unmanned Aerial Vehicle) development by the ILC Dover Company and the University of Kentucky can be found in [5]. NASA has investigated several inflatable aircraft applications, see [6]. Brief information about the evolution of modern inflatable aircraft and pertinent bibliography list is found in reference [7].

The first, and perhaps only, work with inflatable human-powered aircrafts is attributed to Dan Perkins who around 1956 in Cardington, England successively built three prototypes of human-powered aircraft with pressurized wings. Although the first three failed to fly, his fourth and last, the Reluctant Phoenix, flew for the first time in 1965 inside an airships hangar. His first aircraft weighed 28 kg., his last 17.2 kg. See pages 24-27 and pages 67 to 70 in reference [8]. No constructive details were found for the Reluctant Phoenix, though apparently the wing spar and the ribs were made from rigid material.

The reader will find in reference [9] valuable historical, technical and practical information which, in spite of being dedicated to hang gliding, directly relates to the subject of this proposal. A vast amount of recent works demonstrate the high technological maturity level reached by inflatable structures, see references [10] and [11].

It is important to bear in mind that all human-powered flights thus far have taken place near the ground to benefit from the ground effect that reduces induced drag. For example, flying at altitude of 2 tenths of the wingspan, the glide ratio can be increased by 50%, meaning that the power to maintain constant speed level flight would be reduced to 66% of that required for free flight. Therefore, our ultimate objective is to achieve human-powered flight at altitudes greater than 2 wing spans. Until now human-powered flight was demonstrated at very low altitude, about one-half wing span, in almost still air.

Since Icarus and his father Daedalus of legend, human aspiration continues to strive to achieve human flight without the assistance of a catapult launcher, towed launch, cliff or down a slope launch, without ground help to stabilize the wing tip, without storage of energy, only propelled by the muscle power supplied by the pilot to a propeller to develop thrust while reaching sufficient altitude to evade favorable ground effect.

A historical review of human-powered flight attempts is found in references [8] and [9]. The first officially recognized takeoff and landing by the pilot Derek Piggott, took place on 9 November 1961 with the SUMPA (Southampton University´s Man Powered Aircraft). Perhaps the best-known achievements of human-powered flights were crossing the English Channel (35.8 km) by Bryan Allen pedaling the Gossamer Albatross on June 12, 1979, and later on April 23, 1988 Kanellos Kanellopoulos established a distance record pedaling the Daedalus 88 from Crete to Santorini (119 km). Implementation of the herein suggested inflatable structure would reduce the weight of these competition aircrafts. The Gossamer Albatross weighed 32 kilograms and the Daedalus 88 weighed 31 kilograms.

Currently the UK Royal Aeronautical Society organizes two human-powered flight competitions with prizes of £50,000 and £100,000, see reference [12]. The first prize requires competitors to fly approximately 26 miles (41.8 km) in one hour or less. An ultra-light aircraft with a glide ratio of 35:1, powered by an average cyclist-pilot could conquer this mark. The second prize, a sport-oriented competition, requires flying at at least 10 [m/sec] speed for 7 minutes, demonstrating advanced maneuverability capability and disassembly/stowing of the vehicle in 20 minutes.

An inexperienced cyclist can continuously deliver between 50 to 100 watts; an average cyclist can produce 200 watts of continuous power and up to 1,000 watts instantaneously. Some citations [14] indicate that Lance Armstrong, during the Tour de France, continuously produced 400 watts, up to 2,000 watts for a few seconds.

Proposed Inflatable Structure

The examples of inflatable wings cited in the previous section are characterized by being formed by a multitude of inflated (nearly cylindrical) cells of different width extending along the wing span adjacently joined to each other to approximately reproduce a selected airfoil shape, see Figure 1.

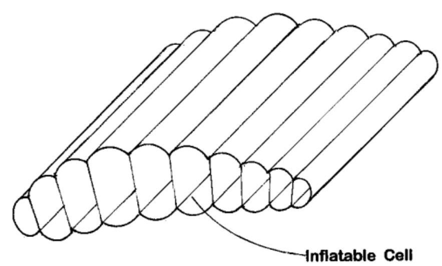

Figure 1. Conventional Inflatable Wing Configuration

The basic concept suggested by this paper is radically different. It consists of an inflatable spar attached to multiple inflatable ribs (similar to a conventional rigid structure configuration) covered by a flexible outer skin resulting into a smooth aerodynamic wing surface, see Figure 2.

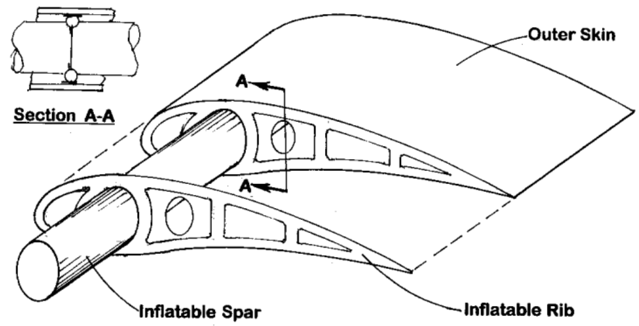

Figure 2. Suggested Inflatable Wing Configuration

A smooth wing surface without ripples yields a fundamental advantage since it eliminates the multiple flow separations originating between adjacent tubes shown in Figure 1. It also allows keeping a longer laminar boundary layer along the wing chord. The concept of Figure 2 in contrast to Figure 1 offers an additional unique advantage; the wing can be constructed with any prescribed twist distribution. This concept requires different inflation pressures; the pressure level inside the spar is relatively high, inside the ribs moderate, and the level to tense the outer skin is relatively low.

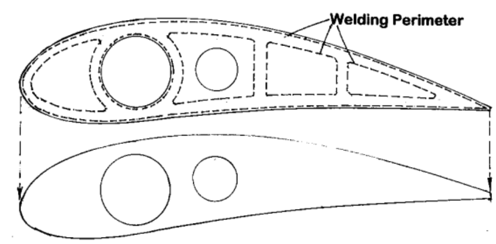

Figure 3. Rib Construction Method

Ribs can be built by imitating the typical lattice of a rigid construction with a circular flange for mounting onto the spar. Each rib is constructed from two flexible and identical sheets welded in multiple perimeters to achieve sealing, see Figure 3.

The spar should be a tapped cylinder (slender truncated cone). Meanwhile the spar is inflated the ribs are joined by adhesive, vulcanization, sewing, thermal welding or combination of these, depending on the material utilized. An assembly fixture is required to locate each rib with the required twist at the corresponding wing span station.

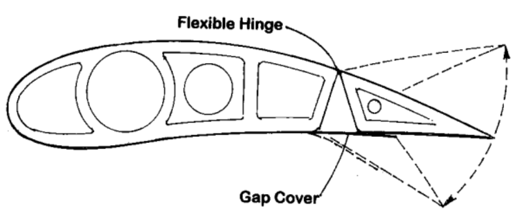

Figure 4. Aileron Configuration

A flexible hinge can conveniently be used to allow rotation of inflated control surfaces, see Figure 4. Forces to move the control surfaces can be transmitted by cable or rod.

In-flight modification of the wing camber is accomplished by cables housed inside of the wing volume using ribs specially designed to yield (crease or partially fold) at strategic points, see Figure 5. Inflatable structures act as a spring, returning to their natural state when these control cables become slack.

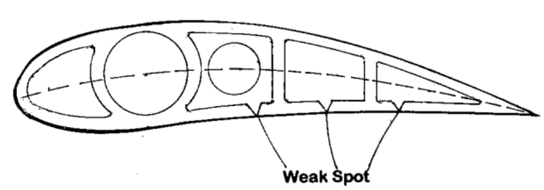

Figure 5. Camber Line Adjustment Method

In-flight camber adjustment (morphing) is very useful, as it allows maximization of the glide ratio during level flight and could replace the role of flaps during takeoff and landing. Camber adjustment should be limited to the wing central area to preserve effective and safe aileron operation.

Inflatable structures are constructed with thin membranes that are flexible and impermeable, from either homogeneous or composite material. Braided fiber reinforcement offers high rigidity and resistance to spars, permitting to tolerate relatively high inflation pressure. Employment of materials whose mechanical properties vary substantially with the temperature should be carefully evaluated or perhaps avoided.

The wing spar is the critical structural component: it must be inflated by a relatively high pressure to sustain the maximum wing load. The weight of the pressurized air entrapped inside the spar could be considerably high, and even unacceptable. To evaluate this probable adverse effect, consider the case of a 15 [m] wing span carrying a 90 [kg] load. By assuming a load factor of 2, a 180 [kg] total load would induce a bending moment at the center of the wing of about 337 [kg.m]. If the wing span is 10 [m] the bending moment would be 224 [kg.m]. A cylindrical spar reinforced with braided fibers requires a minimum inflation pressure to prevent wrinkling at its root (the wing center line) when resisting a specific bending moment.

The following table presents the inflation pressure needed to prevent wrinkling: a value depending on the root diameter of the spar was calculated by an approximate formula suggested in reference [7]. The table also shows both the corresponding volume of the spar (case for wing tip diameter one third of its root diameter), and the weight of pressurized air contained inside said volume.

To the author’s knowledge, there are not load factor criteria applicable to this type of inflatable aerial vehicle. However, an inflatable structure reaching the onset of wrinkles does not yet fail, as it generally tolerates a 2 to 3 times higher load until it folds without breaking. When the load is reduced, it retakes its previous shape.

Spar Root Diameter [m]	**15 meter Wing Span** Spar Root Bending Moment 337 [kg.m]			**10 meter Wing Span** Spar Root Bending Moment 224 [kg.m]			Spar Root Diamete [m]
	Spar Inflation Pressure	Spar Volume	Spar Compressed Air Weight	Spar Inflation Pressure	Spar Volume	Spar Compressed Air Weight	
	[Atm]	[m^3]	[kg]	[Atm]	[m^3]	[kg]	
0,40	1,56	0,91	1,73	1,04	0,60	0,77	0,13
0,30	3,69	0,51	2,30	2,46	0,34	1,02	0,10
0,25	6,39	0,35	2,77	4,26	0,24	1,23	0,08
0,20	12,5	0,23	3,47	8,31	0,15	1,54	0,07
0,15	29,6	0,13	4,64	19,7	0,08	2,06	0,05

The weight increase on an aerial vehicle due to the pressurized air contained inside of the spar might be unacceptable if the goal is a 10 kilogram total weight design. However, pressurizing the spar with helium reduces the weight by 7.3 times.

Selecting a smaller airfoil thickness to increase the wing glide ratio requires a higher inflation pressure for the spar. The adequate inflation pressure for the wing outer skin can be very low because it is not a load-bearing structure. It must keep the wing airfoil shape without deformation. On the bottom surface of the wing, where the local pressure coefficient is positive, the wing's outer skin internal pressure must, at least, match the maximum local external pressure. With a value for the pressure coefficient c_p=+ 1.0 when flying at 150 [km/hr] at sea level, the local external pressure is 0.01 [atm]. The ribs' inflation pressure must be much greater than the wing's outer skin, its optimum value should be determined experimentally considering, among other factors, the range of camber variation desired.

Other design details that may enhance the basic concept are: the use of discrete rigid inserts; utilization of multiple spars; and/or use of tensor lines outside the wing to reduce the bending moment at the spar root.

The above analysis provides an introduction to the basic tradeoff analysis necessary for designing an ultra-light-weight aerial vehicle. Additional suggestions for aeronautical engineering students that would consider embracing this type of project are presented below.

This paper proposes designing human-powered aerial vehicles that have no landing gear: the pilot provides foot-launching by trotting vigorously while supporting the vehicle on his/her shoulder during takeoff and also landing. Such an approach offers these advantages: (1) it eliminates the weight of a landing gear; (2) takeoff and landing terrain surfaces need not be flat and/or smooth; and (3) the pilot can more efficiently accelerate his and the aircraft's mass compared to the use of a pilot-powered propeller to gain takeoff speed.

This concept has been of intersest to the author since having come across a glider in 1954 in Córdoba, Argentina, dubbed the "Piernífero Horten Ho-Xa", designed in 1952 by the late Dr. Reiman Horten, an extraordinary and tireless pioneer for early flying wing aircrafts. The National Air and Space Museum of the Smithsonian in Washington exhibits part of the Ho 229 prototype, an advanced flying wing German fighter plane from the end of WWII designed by him and his brother Walter Horten. A successive glider, the "Piernífero Horten Ho-Xb" was recently geometrically surveyed and its aerodynamic properties estimated by aeronautical students at the Universidad Nacional de Córdoba, Argentina, see reference [13].

Neither of the above gliders was ever capable of man-powered takeoff. The Ho-Xb estimated maximum lift coefficient is C_L=1.14, its wing area is 17.5 [m^2], weights 35 [kg]. A 70 [kg] pilot would need to run at 32.9 [km/h] to conquer takeoff, a requirement that is beyond human ability.

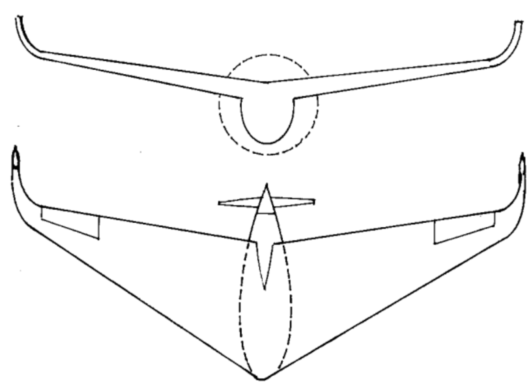

Figure 6. Human-Powered Flying Wing Glider

The world record for speed achieved by an athlete (without carrying and controlling a sailplane and over a short distance) is 10,35 [m/s] (37,26 [km/h]), set by Michael Johnson on August 1, 1996 at the Olympic Games in Atlanta, Georgia running a 200 meter course. Therefore, 15 [km/h] may be a reasonable upper limit for a well-trained pilot to carry and safely control the attitude (angle of attack, yaw and roll) of a very light aerial vehicle.

Two human-powered aerial vehicle concepts are presented for possible student team selection: a flying wing derived from the Piernífero Horten Ho-Xb, and a conventional tail-stabilized configuration.

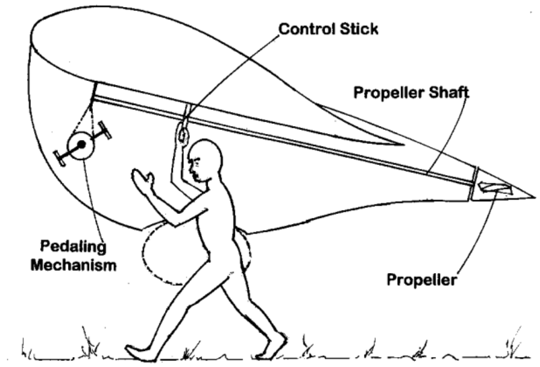

Figure 7. Takeoff Approach

Figure 6 depicts an inflatable flying-wing concept; its hanging gondola enables the pilot to support the vehicle on his/her shoulder, see Figure 7.

In flight the pilot reclines backwards, a comfortable position for pedaling that allows shifting of the center of gravity during flight, see Figure 8.

An ideal design goal would be to attain a takeoff speed V=15 [km/hr] which pre-establishes a dynamic pressure q= 1.084 [kg/m^2]. For example, a glider with wing surface area S=20 [m^2] will require a C_L=2.95 to lift an 80 [kg] load. Such a relatively high C_L level is impossible to achieve with medium-camber airfoil shape without leading and trailing edge flaps assistance.

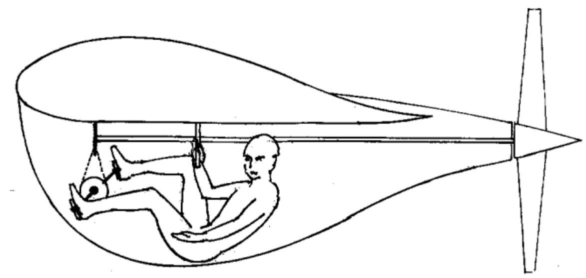
Figure 8. Altitude Flying

An alternative is to increase the wing surface area, however, with a wing span larger than 12 [m] it could be difficult for the pilot to avoid allowing the wing tips to touch the ground during takeoff or landing. This safety concern limits the maximum wing area.

The addition of a retractable tail as shown in Figure 9, deployed only during takeoff and landing in conjunction with camber increase, could be the best solution. This tail performs similarly to that extended by birds during flight beginning and flight conclusion.

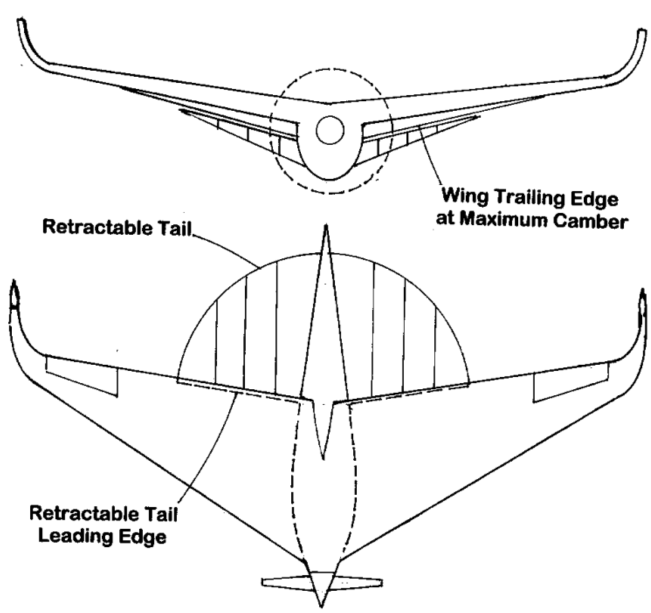

Figure 9. Retractable Tail Fitted into Flying Wing Glider

Although the previous analysis is simplified and speculative, it indicates that it would be possible to design an advanced sailplane or human-powered aerial vehicle that, when including a retractable (or deployable) tail in combination with temporary camber increase, could allow for comfortable takeoff on the pilot's legs.

Should the aim be to purely fly like the birds, we must assume no head wind at the ground level, neither considering exploiting over the edge of a cliff or down a slope launching. Initially, we may need to accept those added conditions until we are able to master design and operation. A quiescent atmosphere is seldom found; therefore a mild and constant head wind without lateral gust should be always acceptable for takeoff.

In designing a conventional (with tail) aerial vehicle, the above-mentioned suggestions also apply, see Figure 10. The wing utilizes a conventional airfoil section unlike the bi-concave camber-line required for longitudinal stability of a flying wing. The airfoils used by the Gossamer Albatross or Daedalus 88 would be adequate as an initial design evaluation.

The author believes that a human-powered vehicle as shown in Figure 10 should perform better than the flying wing concept depicted in Figure 9. For the case of Figure 10, its wing manufacture is simpler than for Figure 9.

The retractable tail, when properly folded against the nacelle or the fuselage, should not increase the parasite resistance of the aircraft. The tail includes a bar that acts as leading edge deployed beneath the wing trailing edge. Tilt or angle of attack of the retractable tail could be fixed or adjustable. Rigid inserts prevent tail fabric dome distortion.

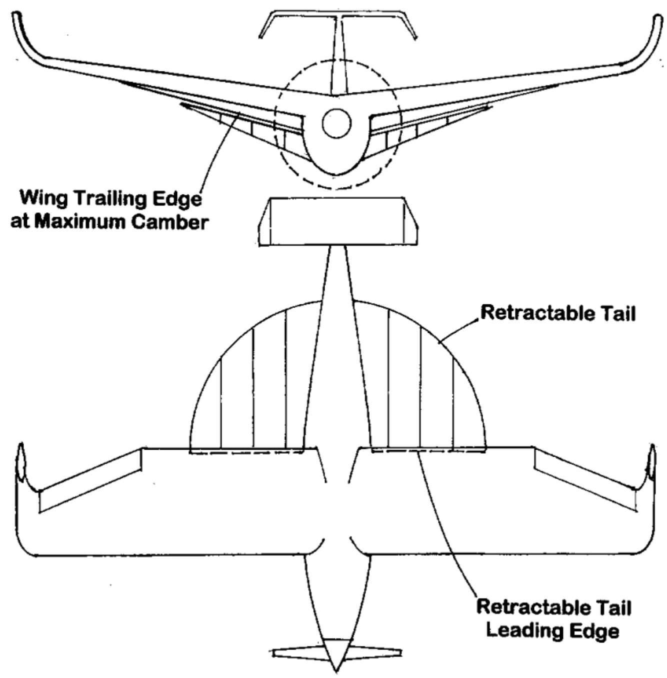

Figure 10. Retractable Tail Fitted into Conventional Glider

Proposed Student Program: Design and Learning Experiences

Although this aircraft has yet to be built, the design described in this paper could be used as an interesting learning experience for students at various levels. For example, for undergraduate students in mechanical/aeronautical engineering capstone design courses, they could analyze the design and assumptions, and try to enhance it. They could also expand the design and explore potential benefits of environmentally-friendly designs or new lightweight materials or control mechanisms.

For graduate-level aeronautical engineering students that have already acquired a sufficient and broad theoretical background, this novel concept could be considered for incorporation into their curriculum as hands-on credit-earning projects (as an elective) that would be of tremendous benefit for their future professional careers.

For multidisciplinary design teams, the above-described novel inflatable ultra-light-weight aerial vehicle concept could be a stimulus for a team of creative and innovative students to undertake the design, manufacture, testing and flying trial of a human-powered aircraft.

The resources required to achieve such an assignment are relatively modest. It is suggested that, after an initial cohort of students has demonstrated the concept as feasible, in following year, subsequent student teams could improve upon the previously developed design and flight operation and perhaps, later participate in an inter-university competition for human-powered flight.

A program to be guided by faculty members should be divided into various phases, for example: initial trade-off design concept selection; computational prediction of aerodynamic coefficients; simulation of flight behavior; development of manufacturing and assembling techniques; aerodynamic, structural and aero-elastic behaviour testing utilizing low speed wind tunnel or a test bed mounted on the roof of a motor vehicle; pedaling mechanism design and testing; and propeller design and efficiency testing.

A test bed mounted on the roof of a motor vehicle safely allows students to exact Reynolds number simulations within a flight regime from 15 to 40 [km/hr] employing a half-wing half-scale model. Concluding tasks would involve: production of final design drawings, aircraft manufacture, quality inspection and initial flight trial utilizing a tow-launch approach without an installed propeller. After probable aircraft modification and incorporation of the propeller, man-powered flight may be attempted. Completing the project may necessitate a two calendar year timeframe.

The program should have a faculty member director that would be responsible for initially organizing the two year project by tasks (each stipulating its credit earning) with full student team cooperation/participation. The mile-stone schedule for each task should be defined a priori, and each task should have a student manager responsible for writing monthly progress reports. The director should be responsible for organizing preliminary, critical and final design reviews.

Once a working concept vehicle has been developed, the possibility would exist for the creation of an inter-university student design contest, similar to current student contests such as the Formula SAE contest [15], or solar-powered vehicles. It is likely that the proposed concept could lead to a variety of viable designs by students, providing ample opportunity for an enduring and exciting student competition.

Conclusion

The purpose of the suggested novel aeronautical engineering student project is to prepare future professionals for typical industry engineering practice. A key goal is to offer students a balanced combination of: engineering disciplines, project management techniques, technical report writing and benefit from team effort interaction. Due to the original nature of the proposed concept, it has not yet been tested, nor has it been implemented in a university or practical setting. Therefore, interested aeronautical engineering programs and their students have the opportunity to contribute to a pioneering concept from its initial stages, an exciting prospect for students at various levels. The author is keen to see the concept incorporated in a learning environment, and would be willing to cooperate with faculty interested in implementing the program at their institutions.

The exciting and motivating components of this project - the novel inflatable structure concept oriented to designing, manufacturing and attempting to fly an ultra-light weight aerial vehicle - should inspire students to persevere into a relatively long, but highly innovative, student project.

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