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The development history of inflated lifting body form LTA vehicle hulls.

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Abstract:

Much work has recently been carried out into the design and development of lifting body form inflated LTA vehicle hulls. This idea is perceived to be relatively new, but has, in fact, a considerable history. This paper reviews some early efforts in this field, and considers what might be learned from them. It then goes on to explore the work carried out in this area over the last ten years by the Tensys design group, of which the authors are members. Early patents, and development of lifting body form theory in the 1950s and 1960s are briefly reviewed. Technical limitations for early designs, in materials and design techniques are considered; as are the technical developments over the last forty years, which have made the idea viable, primarily in materials development, and bonding techniques which have permitted complex forms to be built reliably. Advances in computing hardware and software have led to the ability to model complex non-linear structures with considerable accuracy: some aspects of the analysis and patterning of these vehicles are considered briefly. Commercial confidentiality prohibits detailed exploration of current and future projects, but some activities are briefly reviewed.

1 Introduction

Much work has recently been carried out into the design and development of lifting body form inflated LTA vehicle hulls. This idea is perceived to be relatively new, but has, in fact, a considerable history. This paper reviews some early efforts in this field, and considers what might be learned from them. It then goes on to explore the work carried out in this area over the last ten years by the Tensys design group, of which the authors are members.

Vehicles using lifting body form hulls inflated with helium, and so therefore using a combination of buoyant and aerodynamic lift, have become known as “Hybrid Air Vehicles” (HAV), which term will be used in this paper. The early history of the hybrid air vehicle dates back at least to the 1920s; the perceived advantages of this type of craft fuelled continuing interest, which combined with technical developments, led to many proposals and studies. These are considered at greater length below.

A wide range of factors, both technical and economic, prevented the HAV concept reaching fruition for many years. The technical developments which made the HAV a practicable vehicle concept over recent years are also explored. Economic factors will determine when and if the HAV becomes a widely used vehicle type; these are not within the scope of this paper, but some observations on technical factors are made in the conclusions.

2 Historical review.

2.1 Historic patents

There are a number of patents for hybrid air vehicle schemes, and for some of the associated design ideas which have become part of the current HAV concept, such as air cushion landing systems (ACLS). Some of these are listed below.

Patent# 1656236 – January 1928;
Powelson and Travell
Air Cushion Landing System

Patent# 1686130 – October 1928; Hall
Multi-lobe hullform, with aft mounted propulsors

Patent# 2082376 – June 1937; Boettner
Lifting body hullform with vectored thrust propulsors

Patent# 2091580 – August 1937; Belinski
Lifting body hullform with amphibious capability

Patent# 3180590 – April 1965; Fitzpatrick
Multi-lobe envelope with aft mounted propulsors

Patent# 3486719 – December 1969; Fitzpatrick
Deltoid lifting body with aft mounted propulsors

Patent# 3963198 Jun 1976; Vaughan
Airship ACLS with suction capability

Patent# RE30 129 October 1979; Crompton
Airship with amphibious ACLS

As can be seen from the above, the majority of the elements of the current HAV concept have been under consideration for a considerable period.

2.2 Lifting body development

The above patents relate primarily to HAV design concepts using lift gas and aerodynamic lift; during the latter part of this period, considerable advances were being made in the design and analysis of lifting body hullforms for totally different applications, primarily as re-entry vehicles for re-useable space craft. This work centred on activities at Edwards Airforce Base in California, where between 1963 and 1975, eight different lifting body concept vehicles were flown [1]. All of these vehicle were heavier than air, and were designed for high speeds, but the work carried out at Edwards provided a greater understanding of the behaviour of lifting bodies in flight.

The aerodynamic qualities of these craft were necessarily very different from LTA vehicles, but all exhibited the difficult handling characteristics of lifting body craft, leading to considerable efforts to develop electronically enhanced control systems, which were flown in NASA lifting body craft in 1970. Current HAV projects rely on advanced versions of such systems, with closed loop auto-stabilised systems being used on the most advanced current craft.

Hullform development for LTA craft made little advance during this period, with the only built craft of the time, the Aereon 3 using what were essentially three rigid Zeppelin hulls side by side, and the relatively well known Aereon 26 (“The Deltoid Pumpkin Seed”) [2], using a hullform similar to the NASA lifting body craft. More recent HAV hullforms are very different, as considered below.

The design and testing of the Aereon 26 encountered a variety of the problems that have proven to be inherent in HAV design. In order to minimise the technical issues, the craft was not helium filled, and was simply an “aerobody” – a powered lifting body heavier than air aircraft.. None of the structural and constructional issues which would prove challenging in the later HAV hulls were addressed, but the flight testing of the craft clearly showed the difficult handling characteristics of these type of craft, prone to dutch roll and other control coupling issues. The idea behind the Aereon project was much the same as that of more recent HAVs, but the development was halted by a combination of complex technical issues, and economic problems. This has proven to be a common phenomenon in HAV development.

2.3 Materials and Bonding Technology

Another major group of developments that made the modern HAV hull concept possible was in materials technology and materials bonding techniques. Balloon technology had focussed on ultra-light weight designs, resulting in the highly successful polyethylene scientific balloons, which have no real commonality with airship or HAV applications, but developments in aerostats led to a requirement for high strength fabrics which were also long lived. Since the emergence of the modern non-rigid airship during WW2, hull fabrics had been variations on coated woven materials; by the 1950s, the fabrics used for the large ZPG3W series used Dacron (polyester) base cloths and synthetic rubber coatings, generally Neoprene.

These materials were not highly successful, as the tear strength was insufficient for the large hulls of the ZPG2 and ZPG3 ships (up to 43,000 m3, or 1,500,000 ft3), as shown by the failure in flight of the envelope of one of the four ZPG3Ws, killing 18 of the crew. However, the US military specification for the ZPG2 and ZPG2W fabric – MIL-C-21189 [3] – established the basic rules for airship envelope fabric design, development and testing. The specification called for basic material characterisation tests to be carried out to establish baseline values for the material, and then for a variety of post-processing procedures to be carried out, intended to be representative of the conditions to be experienced by the hull in service. The resulting test matrix gives good data from which the envelope designer may predict the behaviour of the envelope after a defined period of service.

Clearly, in the early days of synthetic fabric development, the experience base was insufficient to provide reliable prediction of envelope lifespan, as evinced by the failure of the ZPG3W hull in the summer of 1960. For many years after, similar un-predicted failures occurred in airship envelopes, due to either incorrect maintenance resulting in degradation that was more rapid than anticipated, or due to a lack of full understanding of the fabric properties or the operating loads. Of particular concern was the susceptibility to hydrolytic degradation of the elastomers used in the manufacture of the fabrics and crucially, in bonding hull components.

For example, the fabrics used by Airship Industries for the Skyship series of airships until the mid 1990s, consisted of a polyester base cloth with a polyurethane coating, which required regular painting to avoid coating degradation, which would in turn lead to UV damage to the base cloth fibres. Insufficiently frequent painting, or painting using incorrect paints and application techniques, led to the premature scrapping of several envelopes. Further, the adhesive used to assemble the envelopes was subject to severe hydrolytic degradation if incorrectly or insufficiently maintained. Again, an absence of complete understanding of the properties of the materials and their behaviour over time resulted in premature envelope failures, fortunately none occurring in flight.

A further issue is that of adequate tear resistance to provide acceptable damage resistance in a large, highly stressed hull. Coated fabric manufacturing techniques require the use of relatively fine-weave base cloths, which cannot provide high tear strength. The achievement of high tear strength in fabrics is generally more problematic than simple tensile strength, and as HAV hulls are generally more highly stressed than those of conventional airships, adequate damage tolerance in an HAV hull requires greater tear resistance, and therefore imposes more challenging fabric requirements.

3 Laminated fabric developments

Clearly, the construction of complex hulls of the type required for HAVs out of the coated type of fabric was neither desirable or feasible for both technical and economic reasons. In order to make HAVs practicable, a new class of envelope fabric was required. During the 1970s, the development of highly resistant materials such as polyvinyl fluoride (PVF – such as the DuPont material Tedlar) enabled the production of laminated fabrics, where a highly weather resistant outer film layer could be laminated to a coarsely woven base cloth, usually made of polyester fibres, using thermoplastic elastomers. These elastomers were usually various types of polyester compounds, such as DuPont Hytrel.

The addition of other advanced film materials, such as polyester film (e.g. DuPont Mylar) to a multi-layer laminate could result in a material with very good properties, combining high tensile strength, high tear strength and excellent weather resistance with good helium retention properties and light weight. Such fabrics were developed primarily in the USA, by companies such as ILC Dover and Westinghouse DESCO (later TCOM LP), mainly for surveillance aerostat applications, where large envelopes with long life were highly desirable.

As part of the laminated fabric development, a new bonding technology was evolved, using the thermoplastic behaviour of the elastomer to permit heat bonding of components. Bonds of this type proved highly durable in service, with no requirement for maintenance or re-bonding.

In the late 1980s, an airship was designed and built using these type of fabrics; the WAI (Westinghouse Airship Industries) Sentinel 1000. This craft was far smaller than the ZPG series, at 10,000 cubic metres, but was the largest airship built since the demise of the large US AEW ships in the early 1960s. The S1000 was designed from inception for construction using laminated fabrics, and was built by TCOM using the same fabric and bonding techniques as employed on the company’s aerostats. The envelope had some minor ballonet issues, but the hull was essentially trouble free from first flight in 1990, until the airship was destroyed in the Weeksville NC hangar fire in 1995.

The final significant development in fabric technology has been the increasing availability of high tenacity fibres, the use of which permits greater tensile strength to weight, and also greater tear strength to weight. Fibres such as Spectra, Vectran and Kevlar all offer various advantages in terms of strength and durability, but all have various disadvantages which must be taken into consideration in the design process.

4 Analysis techniques

The construction of complex hull forms has only become realistically possible since the development of computer based finite element modelling techniques. Traditional body-of-revolution airship envelopes were built using simple stress calculations, based almost entirely on the level of hoop tension due to inflation pressure; long experience showed that a fabric and a hull designed for hoop tension was generally capable of resisting other loads applied to it. Clearly, this is not the case for a hull designed to provide significant quantities of aerodynamic lift from an elaborate hull form. An additional issue is that of patterning complex hull forms; a traditional “cigar” shaped airship envelope may be patterned using the simplest of techniques, whereas developing patterns from a compound curved hull form requires considerably more complex processes.

4.1 Development of FE Analysis

The development of finite element analysis (FE) techniques in the 1950s and 1960s by those such as Ray Clough and Edward Wilson at Berkeley [4] opened new possibilities for all forms of structural analysis. These techniques were derived from various different techniques and approaches, but all involved the reduction of a structure to a mesh of discrete elements, frequently triangular in plan, loads and deflections for which could be solved individually. Aeronautical and space engineering problems were key drivers of these techniques, with NASA initiating the development of the FE software NASTRAN in the mid-1960s. Sound mathematical foundations for the technique were in place by the early 1970s, allowing the development of commercial software packages as higher performance computer hardware became available.

FE code was generally developed for conventional engineering structures such as aluminium airframes, and steel bridges, where displacements are usually small and the relationship between stress and strain is broadly linear. Fabric structures, by their nature, involve large displacements, and non linear characteristics; to this day, many mainstream commercial FE packages do not handle fabric structures satisfactorily. As large scale fabric architecture became more popular in the 1960s and 1970s, there was a clear need for FE techniques that could solve these problems; early large scale fabric structures were frequently designed by constructing large scale cable net models, which was expensive and time consuming.

4.2 Development of FE for fabric structures

Accordingly, a number of attempts were made to develop FE techniques capable of analysing fabric structures. Engineers such as Frei Otto, Ove Arup and Edmund Happold were key in developing these techniques, with their respective companies becoming major players in the field. The mathematics were fully in place by the 1970s, but practical applications were limited by the available computer hardware. A technique known as Dynamic Relaxation (DR) had proved to be effective in the form finding and analysis of fabric structures, accommodating large displacements in the establishment of an equilibrium form from defined boundary and loading conditions, whilst also retaining problem sizes capable of being handled by the computer hardware then available, and which were linearly related to the problem size.

A PhD thesis on DR was written in 1980 by Dr David Wakefield [5], who became Director of Computing for Buro Happold. Dr Wakefield then started Tensys Ltd., in 1990, to carry out form finding, analysis and patterning tasks on fabric structures. The suite of software programmes that have become inTENS were developed during this time, initially solely for architectural applications. In the early days, the capabilities and cost of the available computers were the chief limitations. A Sun Sparc Station 1 was the first machine owned, at great cost, by the company; the rapid developments of computer hardware, particularly PCs, during the 1990s permitted an equally rapid expansion of the capabilities of software. As the complete software package was designed and conceived specifically for fabric structures, and as it is written and developed in-house, considerable flexibility in expanding and optimising the capabilities of the code were available.

4.3 HAV projects using inTENS

This software was first used for patterning a part of an LTA vehicle in a small task for the Cargolifter demonstrator, in 1997. In 1998, Advanced Technologies Group (ATG) were contracted by Lockheed Martin ADP (the Skunk Works) to design and construct a scale model demonstrator of one variant of the LM Aerocraft concept. This was a tri-lobe, lifting body hullform, consisting of three cambered hulls of modified ellipsoidal form, merged together. As this was a small scale model of only 37m3 volume, no great analysis was required, but the accurate patterning of such a hull was relatively complex.

Accordingly, ATG approached Tensys to carry out this work; the hull was patterned, and constructed in late-1998, flying several times shortly afterwards. The hullform of this craft was very different from the NASA lifting body forms developed in the 1960s, as it was clear that the requirements for a low speed terrestrial craft were wholly different from those for high speed re-entry craft – the intended purpose of the NASA concept vehicles. Traditional aerodynamic theory for low speed airfoil design was applied to the problem, resulting in relatively conventional very low aspect ratio airfoil shapes; LM initiated CFD modelling of these type of forms during the Aerocraft programme, laying the groundwork for later developments in optimising HAV hulls. The Aerocraft demonstrator, however, was not subject to rigorous aerodynamic analysis, but was rather designed as a simple test vehicle, capable of rapid construction. The modified tri-lobe ellipsoidal hullform worked, but showed some of the problematic characteristics that would later have to be resolved, in particular considerable pitch instability.

The Aerocraft programme was cancelled in 1999 for a variety of reasons, primarily economic. Further developments of what became known as the “SkyCat” concept were pursued by ATG, resulting in two scale model demonstrators, the so-called “Sky Kitten” craft. The envelopes of both of these were analysed and patterned by Tensys, the first envelope being built by ATG in 2000, and the second by TCOM in 2001. Both of these envelopes were of modified ellipsoidal, cambered tri-lobe form; both also used a structurally tidy, but aerodynamically undesirable form of nose construction, where the outer hulls were wrapped around the front of the hull, leaving a marked dip in the profile, normal to the airflow. “Sky Kitten 1” made multiple flights during 2000, with considerable success.

During the design and development of these craft, a wide range of features were added to the inTENS software, resulting in an ability to model accurately helium lift, air masses in ballonets, point loads, applied pressure loads from CFD, etc. Continuous development of the software has carried on to date, with features being added as required. Advances in patterning techniques have also been made, although successful patterning relies on accurate test data for the biaxial properties of the hull fabric, and a certain degree of interpretation. Efforts are continuing to develop patterning tools such that an intended initial hullform may be approached as closely as possible in the final, helium-inflated, stressed vehicle form.

4.4 Hullform optimisation

Techniques have been developed over the last decade to permit the iterative development of hullforms using CFD. Clearly, this requires considerable programming and computing resources, and is an approach only feasible for major, well funded organisations. This work is proprietary, and is not within the scope of this paper.

5 Recent developments

The latest developments in modelling techniques are necessarily subject to commercial confidentiality, but Tensys have continued to work with LM and others to analyse and pattern HAV hulls and a variety of other LTA vehicles. The successful LM P791 demonstrator is still not open to public scrutiny, but images may now be found on the internet.

Development in control systems and in hullforms have permitted considerable theoretical advances; no craft has yet been built incorporating these features. Optimisation of hullforms reduces the control requirements, and advances in control software, air data sensors and auto-stabilisation systems provide greater ability to control the aircraft.

6 Future developments

Future progress in structural and manufacturing design is expected to involve, among a wide range of developments, the greater integration of analysis and the manufacturing and patterning processes. Relatively recent developments in high performance fabric, or perhaps more accurately, soft composite, manufacturing techniques have included the 3DL process, devised by North Sails, for the manufacture of high-performance racing yacht sails. This process involves the use of an adjustable three-dimensional former, over which a film is laid, with fibres then being laid down in groups or individually, along trajectories directly derived from the stress analysis. This approach completely avoids the use of woven fabrics, cut into panels or gores, and results in flexible composite panels which have the structural fibres where they are required, in the required orientation. This process is not yet suitable for

HAV hull manufacture, but shows strong promise for the future.

7 Conclusions

If the economic viability of the large HAV is demonstrated, the technical capabilities to design, analyse and construct the hulls of such craft are available. Hull form optimisation programmes reduce the inherent instability issues, and control software advances permit the development of craft with acceptable handling characteristics. FE analysis techniques have developed to the point that hull structures may be analysed with confidence, and patterned with a high degree of accuracy. Developments in high strength fibres and highly weather resistant films have provided the basic materials needed to build such hulls, and the development of capabilities such as the 3DL process has shown how such hulls might be constructed more efficiently.

References:

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