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Structure Design for the Elettra Twin Flyer Prototype

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I. Introduction

The low-cost multi-purpose multi-mission platform Elettra-Twin-Flyers (ETF) is being developed by the synergy of Nautilus S.p.A and the Politecnico di Torino[1]. It is a very innovative remotely-controlled airship equipped with high precision sensors and telecommunication devices. For its peculiar features, it is particularly suitable for inland, border and maritime surveillance missions and for telecommunication coverage extensions, especially in those areas which are either inaccessible or without conventional airport facilities and where the environmental impact is an essential concern. ETF is characterized by great manoeuvrability as well as low wind sensitivity[2]. Flight conditions range from forward, backward and sideward flight to hovering, both in normal and severe wind conditions. To achieve these capabilities the ETF has been conceived with a highly non conventional architecture. The key point of the design is the innovative command system, which is completely based on thrust-vectoring propellers moved by electrical motors, powered by hydrogen fuel cells. The ETF concept comes from surveillance and monitoring purposes. The airship is designed to have great manoeuvrability to meet high level mission requirements, set to operate highly specialized instrumentation, such as light Synthetic Aperture Radar (SAR) systems or Electro-Optic (EO) infrared cameras or hyperpectral sensors. To fulfilling the average surveillance requirement, the system has a minimum endurance target of 48 hours with extension to 72 hours, with an altitude operation ranging from 500 to 1500 meters.

Flight tests are in progress on a flight demonstrator[3], which is a reduced-scale reduced-complexity platform, purposely assembled to test the most critical subsystems, such as the command system and the architectural solution. Ground and flight tests are revealing that the architecture can be further optimized. For this reason the whole configuration is being reconsidered. Different architectures have been proposed and they are now being analysed under manifold points of view.

This paper presents different structural solutions compared under the same manoeuvrability and operativity requirements.

The structures to be analysed are chosen from an initial set, selected among many solutions which fulfil the dimensional requirements. The airship, in fact, has to be big enough to accommodate a pre-determined volume of payload, has to accommodate the motors in pre-defined locations to allow a good manoeuvrability while limiting the structural deformations, must be able to house all the systems necessary for its operation and should be able to contain enough volume of helium as to sustain at least the 95 % of the structure weight.

To minimize the costs of the structural analysis two configurations has been selected as the most representative of the many configurations proposed: the non-rigid double-hull (Figure 1) and the rigid soap-shape airship (Figure 2). Among
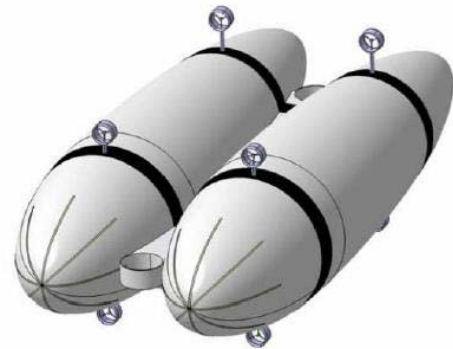

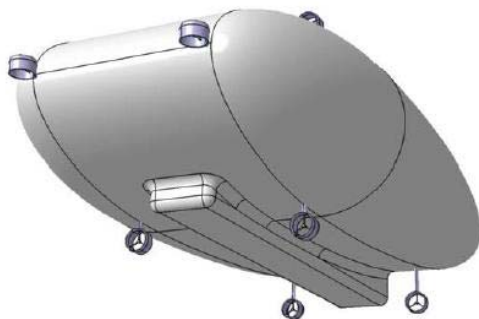*Figure 1 – Non-rigid double-hull configuration*

the available aeronautical technologies, the aluminium truss and the carbon sandwich structures have been considered for the exoskeleton of the soap-shape airship. On the other hand, the structure of the double-hull is too complex to be realized by standard aluminium components, so only the carbon sandwich solution has been analysed.

During the feasibility study many aspects have evaluated beyond the structural one. These aspects have been analyzed not only as independent problems, but also and especially for the impact they have on the structure and on the consequent choice of configuration. The comparison analyses have always been conducted in the respect of the control architecture geometry. The main constraint, in fact, is the control

Figure 2 – Rigid soap-shape configuration

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[2]Associate Professor, Aeronautical and Space Department, piero.gili@polito.it
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architecture which makes use of trust-vectoring propellers. It must be considered that, to some extent, the command strategy uniquely defines the number and position of the engines, according to the configuration of the demonstrator which is currently being tested (Figure 3). As a consequence, the same constraint imposes load positions as well as weights for the auxiliary systems and for the onboard power unit.

As the platform is unmanned, however, it allows a simplified design since there are no constraints related to the ergonomics of the pilot and passenger compartment. This feature has mainly two implications: first, it is not necessary to provide the structure with openings and windows to give the pilot visual field, since the visual feedback to the pilot located in the ground station is usually provided by video cameras, which can also be accommodated outside; secondarily, the absence of the pilot offers higher volume capabilities for the accommodation of the auxiliary

Figure 3 - The Nautilus ETF demonstrator

devices or payload. The on-board systems are also greatly simplified and reduced. The considerable amount of volume available on the ETF has permitted the evaluation of different solutions for the energy storage, namely the storage of hydrogen necessary for the operation of fuel cells. In this context it is worth pointing out that it was the technological limitation imposed by the power generation that has generated the most stringent requirements for the architecture definition. These requirements may be translated into a twofold specification: on one side it is necessary to minimize the structural loads, converging to the lightest structure without reducing the hydrogen stored, on the other side it is crucial to maximize the amount of hydrogen to provide competitive endurance.

II.   Power generation

As already mentioned, a crucial aspect in the ETF design is the substantial amount of the internal volume. This is useful for two reasons: it allows, first, a more distributed allocation of the onboard systems, thereby avoiding concentration of loads, second, the evaluation of different solutions for the hydrogen storage.

The hydrogen storage is troublesome in many applications: hydrogen surely has a very favourable energy density, in fact, but the ratio volume per unit of energy becomes comparable with more conventional fuels only if it is stored in high pressure tanks. This is crucial in certain applications, such as in the automotive or aerospace field, where the volume of fuel must be limited to maximize the payload capabilities. Moreover, it is clear that the presence of a high pressure tank can be considered an additional element in the fulfilment of the safety requirements. This is particularly evident for the automotive market, for example, where the tank must be designed to resist not only to the internal pressure, but also to the impact loads generated by a crush. The latter requirement is by far the more stringent for storage pressure lower than 200 atm. This means that even if there is an extra availability of volume, there is no convenience to store the hydrogen at pressure values lower than 200 atm. This consideration might partially solve the problem of the energy density (namely volume per unit of energy). On the other hand, what still needs to be increased is the ratio of energy stored on total weight, where *total* stands for fuel and container: for hydrogen fuel cells, in fact, it is currently about 0.75 kWh / kg. This value might be acceptable in the automotive applications, but in the aerospace field the requirements are more stringent, especially for high endurance vehicles.

For the specific case of the ETF, the board fuel volume is not an important constraint, whereas the reduction of the total weight is obviously critical, as in every aeronautical applications. This is the reason why an alternative storage technology is being considered. Among the other options, the huge available volumes suggest the gaseous hydrogen could be easily and safely stored in low-pressure light-weight tanks, which could be embedded in the helium envelopes. This expedient could be very effective to diluted potential hydrogen losses, reducing the risk associated to a highly explosive gas. In this context, the technology is still not very developed, given the limited industrial interest. In order to investigate the possibility of adopting this solution for the ETF, a test bed has been assembled to test fuel cells fed with hydrogen at atmospheric pressure. The main problem is constituted by the compressor, which should be used to supply the fuel cell with a specific operative pressure, compressing the gas stored at atmospheric pressure. The employment of a compressor is uncommon in fuel cell systems, because usually the hydrogen is withdrawn by high pressure tanks (200-600 bar) and the pressure is then reduced in accordance to the anode specifications.

This technology, applied to the ETF prototype, could lead to a reduction of several hundred kilograms: for the ETF: it has been estimated, in fact, that the high pressure tank weight would be alone more than 80% of the weight of the whole fuel cell supply system. The low-pressure light-weight tank solution could be very effective in reducing weights and dangerous concentrate loads on the structure. It must be considered, however, that the hydrogen stored at atmospheric pressure produces extra buoyancy which must be balanced with ballast. To this purpose, water could be safely used. It could be stored in tanks and vaporised at a specific rate to equilibrate the loss of buoyancy due to the hydrogen consumption.

As already mentioned, the hydrogen containers could be inserted in the hulls. In this case the hulls should be provided with a ballonet system purposely designed to accommodate external air, to compensate for the hydrogen consumption. The same ballonets could be used as a common lighter-than-air compensation system, to maintain a constant buoyancy and avoid potential helium losses which could be consequences of dramatic changes in the external conditions or simply induced by altitudes variations.

III.   Envelope

As above mentioned, two different structural solutions have been considered. For the double-hull configuration the envelope material must be able to satisfy both the structural and helium retention specifications. In this case, the structural loads are determined by the internal overpressure, but also by the stresses arising from all the applied loads.

Moreover, the same material must also be characterized by high resistance to external agents and in particular good tolerance to aging factors such as UV rays. It should be able to dissipate static electricity and should have low predisposition to water retention. To this purpose the most suitable solution could be a multilayer laminate, consisting of a structural fabric coated with several films, which confer the envelope the required characteristics.

Experience has shown that a multilayer envelope is the best solution for a non-rigid airship, in particular to resist the high concentration of stress which can be detected in the area of the connection between the envelopes and the central structure.
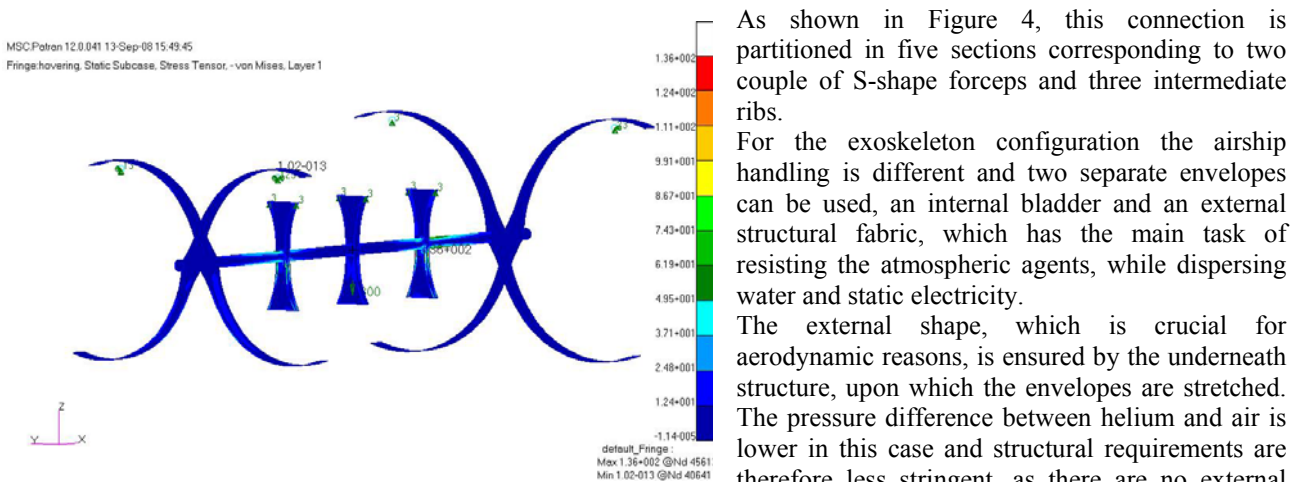

Figure 4 – Structure analysis for the double-hull configuration

As shown in Figure 4, this connection is partitioned in five sections corresponding to two couple of S-shape forceps and three intermediate ribs.

For the exoskeleton configuration the airship handling is different and two separate envelopes can be used, an internal bladder and an external structural fabric, which has the main task of resisting the atmospheric agents, while dispersing water and static electricity.

The external shape, which is crucial for aerodynamic reasons, is ensured by the underneath structure, upon which the envelopes are stretched. The pressure difference between helium and air is lower in this case and structural requirements are therefore less stringent, as there are no external forces applied directly to the fabric. The internal bladder must simply contain helium. There are not structural requirements on it, apart form resisting to the friction caused by the contact with the outer structure, on which the bladder transfer the aerostatics loads. The bladder should be prevented from having concentrate contact points with the carbon or aluminium exoskeleton structure. For this reason the inner bladder is constrained in a net which is interposed between the structure and the same bladder. The net function is twofold: on one side it has to protect the bladder from the concentrate stresses which are critical for the bladder integrity, on the other side it helps in distributing the buoyancy uniformly on the exoskeleton segments, which are the only structural element of the airship.

IV.   Load definition

The two different structural solutions, which have been considered, have the same tasks, namely: they have to transmit the whole airship the maneuvering actions generated by the trust-vectoring propellers, collect the aerostatics forces generated by the helium and provide the onboard systems, payloads and power unit with the appropriate attachment points and housing.

The command system action is perpetrated by the forces produced by the propellers, which have to generate high rotational moments. For this reason they must be positioned far from the center of gravity. Therefore, the main problem associated to this kind of structure is not the stress level, but the high consequent displacements. Both solutions, thus, have to be dimensioned under the constraint of maintaining the applied forces at fixed positions, to
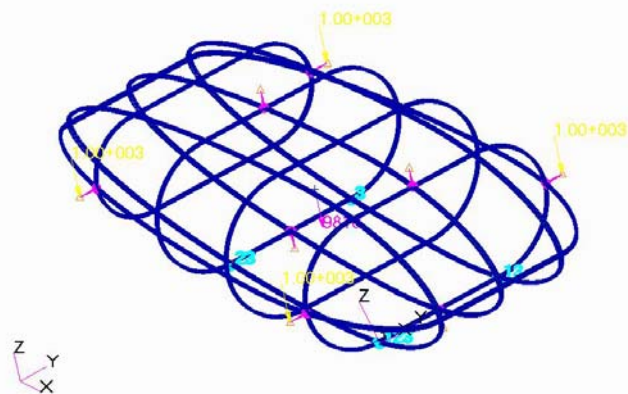

Figure 5 – Exoskeleton for the soap-shape configuration

ensure a correct control action. The resultant structure is then characterized by high rigidity and very low stress levels. For the double-hull solution, the envelope are connected to the structure in five points along the longitudinal axis: the two couple of front and rear S-shaped clamps and three intermediate ribs. The hulls are secured to the structure through straps, which are fastened at all the five connection points. In this way the more critical loads, which are brought about by the buoyancy, can be uniformly distributed along the belt main resistant direction, whereas the aerodynamic forces are transmitted to the S-shaped structures. The same structures prevents the hulls form being pushed and eventually unhinged from their location. The aerodynamic drag, in fact, is contrasted by the belt friction and, more important, by the clasp action performed by the counteracting Ss which embrace the hulls on the two sides of the maximum diameter section.

For the soap-shape exoskeleton configuration the closed structure is certainly more effective in contrasting the external loads (Figure 5), meaning that under the same maximum stress, the deformation picks are reduced.

A first preliminary analysis has brought to the selection of light solution of T-section spars and ribs. This choice has proven beneficial in terms of weight, but not in terms of local stresses and deformations. A consequent optimization study has been performed to identify the best section shape, featuring low weight per unit length and high inertia at the same time. The closed square section has been selected as the most suitable.

For each airship configuration the minimum feasible length has been calculated. To this purpose, an iterative approach has been used to define the weight components. Some of them, in fact, depend on the airship overall dimension and weight, being the latter a function of the structural weight. For both the configurations the iterative procedure has been triggered assuming for the airship an overall dimension; the weight has been consequently estimated to evaluate weights and dimensions of the subsystems. Multiple iterations have brought to reach a convergence value for each airship length. Increasing the overall dimension, the minimum feasibility value has been easily determined. The buoyancy, in fact, which should contrast the airship weight, increases proportionally to the length cube, whereas the structural weight increases roughly with its square.

The two configurations are both parameterized with the airship length. As already mentioned, depending on the overall dimensions, in fact, the weight of some components can vary considerably. In particular:
• the landing gear weight is estimated as 15% of the total weight;
• for the power unit, the ratio weight on power is considered constant whereas the trend of the required power is assumed proportional to the airship moments of inertia;
• the weight of the systems is estimated from empirical data as a function on the onboard power;
• for the propulsion electrical motors the weight / power ratio is considered constant;
• as for the envelope weight, previous experience and data taken from the state-of-the-art surveys suggest specific values of about 200 gr/m^2 for the soap-shaped configuration and 300gr/m^2 for the double-hull;

To minimize the calculation costs, the structural analysis has been restricted to the most severe load conditions, which have been selected through the analysis of the operative conditions. This preliminary feasibility study has thus revealed that 36 and 31 meters are the minimum airship lengths respectively for the double-hull and soap-shaped configurations (see Figure 6 for a comparison).

An important factor is the dynamic structure behavior, the impact of which has been investigated since the preliminary stage. The first step is, of course, the determination of the structural natural modes and frequencies, to monitor and prevent dangerous interactions between low frequency structural vibrations and unsteady aerodynamic phenomena. The aerodynamic analysis, in fact, has shown that a critical situation might arise in hovering with lateral wind, when a vortex phenomenon is detached at a relatively low frequency
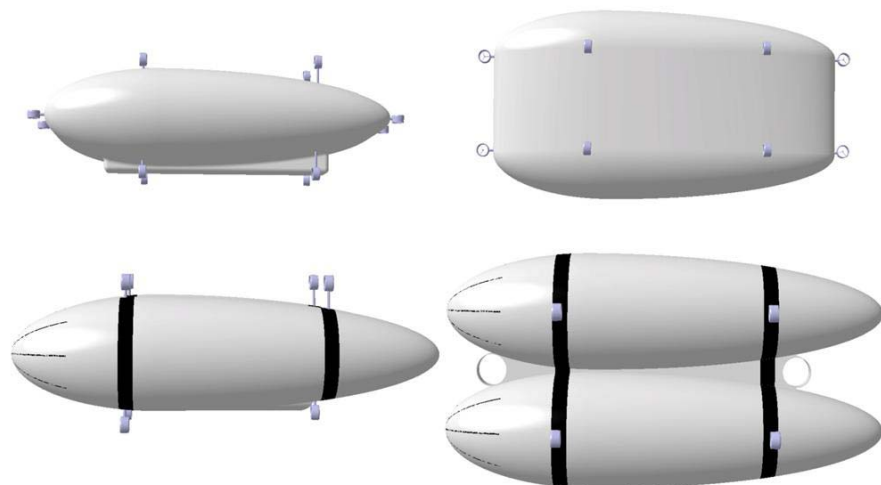

Figure 6 – Dimensional comparison between the two Nautilus ETF configurations.

(0.3 Hz). Motors and propellers could affect the structural analysis with their rotational speed and could potentially modify the structural modes or give rise to resonance problems. These effects however, have been neglected in the modal analysis.

The nonlinear analysis has been introduced for specific load conditions, when the structure does not comply with the conditions of linearity. These load conditions have been analyzed imposing a solution based on the non-linear displacements equations. This approach has not been used since the very beginning as it implies computational costs significantly higher than the linear approach. It was therefore decided to preliminarily evaluate the scale of displacements in every single case and then refine the analysis with the non-linear equations only in specific situations.

The obtained results reveal a high stiffness of the analyzed structures. This implies that an optimization process should

Figure 7 – Soap Shape solution – Hovering load case

definitely be evaluated. If we consider, for example, the soap-shape configuration in hovering (Figure 7) we notice that strains are very limited, if compared to the overall exoskeleton size.
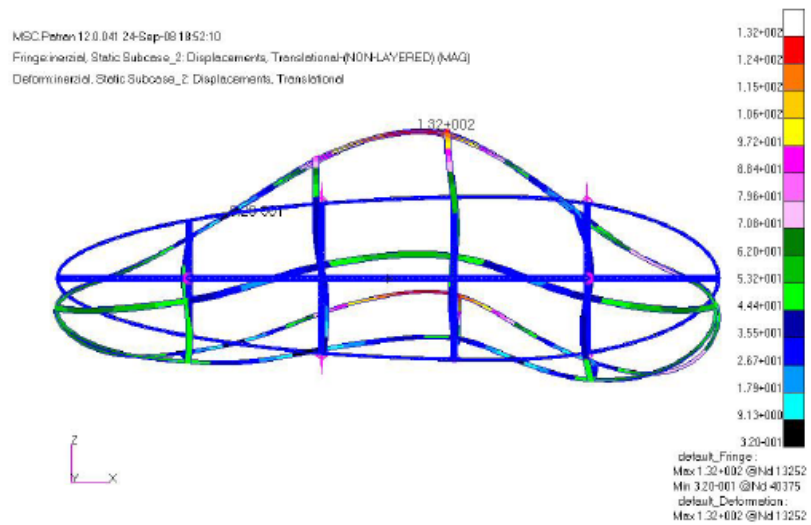
A major contribution undoubtedly comes from the inclusion of guy-ropes that allow the distribution of the ventral loads on the dorsal structural components.

The same conclusions apply to the double-hull configuration, for which the loads transmitted from the hulls to the saddles do not cause strain and stress levels to an extent that could compromise the structural integrity, as shown in Figure 8. It is therefore clear that the structure is strongly overdimensioned and must be lightened. For the double-hull configuration, the performed analysis does not have highlighted abnormal loads concentration. The anomalous loading concentrations of the soap-shape structure, on the

Figure 8 – Dual Hull solution – Hovering load case.

other hand, are only due to the lack of detail in the connection modelling. A very simple model, in fact, has been preferred in this early phase of the design, when it is important only to simulate the load transmission through the ventral/dorsal guy-ropes. Connections will be further detailed in a more advanced design phase while, at this point, the concentrated reactions are simply tolerated as a normal consequence of a poor modelling.

The analysis of the contribution and interaction of the inflated envelopes on damping and stiffness is currently in progress.

V. Logistics

Always from the perspective of the preliminary analysis, handling and transportability have been considered as decisional factors. For an object of at least 30 meters of length the assembly procedure must be carefully examined and planned. Transportation is also troublesome, unless the components are stored in proper containers which can be moved through standard vehicles. For the soap-shaped configuration the resultant optimized structure is a closed truss shell and

must be divided into several pieces to be stored. To create the appropriate joints the structure must be purposely modified with a consequent weight increment.

Even from a manufacturing point of view, it must be considered that the structural components might be very large, for example a considerable amount of pieces could exceed 15 meters of length. Some of them might be divided and manufactured in smaller pieces: large autoclaves are hardly available and the use of a vacuum bag, instead of an autoclave for the material polymerization, could reduce the overall structural quality. Nevertheless, large components require special transport vehicles, and the risk associated to the handling of long and cumbersome pieces must also be taken into account.

For the double-hull configuration the structural components are fewer and smaller. The three central ribs, the S-shaped clasp and the central structure could be easily taken apart in pieces and transported in standard size vehicles. Obviously, some parts of the structure cannot be separated or divided as joints may jeopardize the correct functionality.

Portability is a crucial aspect, but also assemblage complexity should be taken into consideration. The double-hull configuration needs assembly support facilities which are much slender and simpler than the ones that should be used for the rigid airship. The latter in fact, is not manageable without the support of a large scaffolding, as the exoskeleton is self-supporting only when it is completely closed. Until all the spars are not closed on themselves, in fact, they do not cooperate in supporting even their own mass. Hence, the necessity of the supporting structure. The light frame required to hold the double-hull components, instead, are simply used to keep the central structure at the right vertical height. Ribs and clasps do not need to be supported and can be mounted on the central structure afterwards.

It is clear that size and complexity of the infrastructures are very different. As for the transportation, thus, the assemblage complexity may affect the final choice. Regardless which configuration is selected, however, it has been decided to concentrate the onboard systems in a single cargo bay, to reduce the areas to which access needs to be guaranteed for inspections and maintenance.

VI. Costs

Last but not least, an important factor which must be considered to select the best structure is the component production cost. The analysis is not elementary as the technologies involved in the manufacturing process are very different for the two configurations.

For the soap-shape model, the structure is an assemblage of a large amount of elements, which, however, require a limited number of molds, as the element geometry is repetitive. For this configuration the most critical factor in the cost determination is the high amount of carbon, while costs related to the molds are relatively low.

On the contrary, the double-hull configuration has a low number of components which are obtained with highly specialized molds. Saddles, namely the components used to connect the two hulls to the central structures, need very large molds. They must be specialized, at least one for the front and one for the rear part, as the hull geometry is not symmetrical, for aerodynamic reasons. On the other hand, the manufacturing of the mold for the shaft will be particularly critical and will require the same technology employed in the production of space tanks.

This kind of mold, in fact, must be purposely tapered in order to facilitate the piece extraction at the end of the process. In particular, the level of superficial roughness must be considerably low, which necessarily involves the employment of numerical control machines. This problem could be overcame by adopting a different section shape, which however implies a reduction of torsional stiffness.

These considerations must be weighted and analysed to estimate the real impact of molds in mass production. Considering the expectations of production for this platform, it is clear that the double-hull would be more cost effective, even if the prototype costs seem more favourable for the soap-shape. Once the mold cost has been paid off, in fact, the main cost for the structure manufacturing would be the row material, which is considerably lower for the double-hull as it implies a smaller amount of carbon.

VII. Conclusions

The study analyzed in this paper has highlighted the peculiarities of the two configurations. They have been compared in terms of cost, development and manufacturing characteristics. Each configuration has features that make it successful,

Figure 9 – Non rigid soap shape.

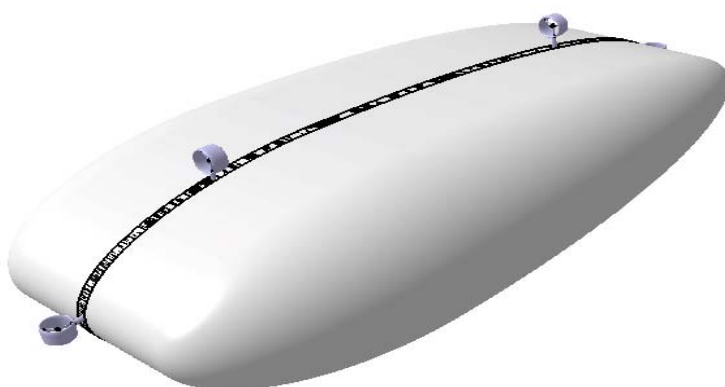but not enough to make it preferable to the other. As a consequence, a third solution, the non rigid soap-shape, is being

analysed, as a compromise to combine the advantages of a small dimension carbon fiber structure with the best aerodynamic characteristics of the soap-shaped solution.

In this case the structure would be composed of a single longitudinal rib placed in the *XZ* plane. The rib task is to contain the soap-shaped hull, collect the loads deriving from the ventral nacelle and from the propellers, all placed on the rib itself (Figure 9).

A further analysis should be performed considering the structural contribution provided by the pressurized envelope,inserted within the carbon structure.

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