Morphing Conceptual Design – A320 Vertical Tail

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Às minhas avós Brasilina e Leonor

Aos meus avôs Brandão e Melo

Aos meus pais e irmãs João, Dulce, Rita e Maria

Pelo seu exemplo, por tudo o que me ensinaram

e por poder contar sempre com todos.
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Resumo

Nas últimas décadas, uma procura crescente de voos comerciais juntamente com uma acrescida preocupação ambiental desafia a indústria aeroespacial, exigindo aeronaves com maior eficiência e menores taxas de consumo de combustível por passageiro. Uma oportunidade de melhoria foi identificada na cauda vertical da aeronave AIRBUS A320, onde um substituto mórfico poderia contribuir no sentido de aumentar a sua eficiência.

Várias estruturas mórficas foram estudadas, baseadas em diversas tecnologias recentes, contudo, apenas algumas poderiam ser certificadas e implementadas em aeronaves civis. Foi gerado um conjunto de soluções mórficas e efectuado um estudo comparativo, tendo sido seleccionado um conceito baseado na flexão de uma casca em material compósito laminado.

Os grandes deslocamentos característicos deste movimento mórfico induzem extensões elevadas no material, sendo necessárias várias análises para garantir a viabilidade da solução. A casca foi analisada em FEM, tendo sido escolhido uma modelação simplificada em faixa. A natureza do problema implicou a utilização de uma análise Não-Linear.

As formas geométricas mórficas obtidas foram comparadas com aquelas que servem de referência e as propriedades mecânicas comparadas com os valores tabelados, quando a casca é simultaneamente flectida e carregada aerodinamicamente. As zonas com maiores extensões foram identificadas, assim como o comportamento característico da estrutura. Um processo de optimização foi adoptado a fim de reduzir o peso estrutural.

Esta investigação prova que os materiais actualmente certificados pela AIRBUS podem ser utilizados nestas estruturas, substituindo a actual configuração do leme de direcção e contribuindo também para um conhecimento aprofundado do comportamento de placas de compósito à flexão.

Palavras-chave: morfismo, bordo de fuga mórfico, flecha variável, estruturas mórficas, estabilizador vertical, leme de direcção
Abstract

In the last decades, flight transportation has grown and environmental requirements have become more stringent. This challenges the aerospace industry to design more efficient aircrafts with lower fuel consumption per passenger. An improvement opportunity was identified on the Vertical Tail of the AIRBUS A320 where a morphing design of the rudder could contribute towards these objectives.

Several morphing concepts exist based on state-of-art materials and technologies but just a few could be certified and implemented on a civil aircrafts. A group of morphing rudder solutions was created and a trade-off analysis performed. A conceptual design based on a composite bended skin was selected for further investigation.

The large displacements involved in this morphing movement induce high strains in the material and further analyses should be performed to check the feasibility of this design. For this, the skin was modelled and studied in detail with 2D FEM Strip Models. The nature of the problem implies a Non-Linear Geometric FEM analysis.

The morphed shapes obtained with the analysis were compared to the target ones. Furthermore, the most important allowables were checked for the composite skin under bending and air loading. The locations with highest strains were identified as well as the structure characteristic behaviour. An optimization process was done in order to reduce the structural weight.

This research proves that current AIRBUS qualified materials can achieve morphing, in the case of the A320 VTP, and contributes to a better understanding on the behaviour of bended composite plates.

Keywords: morphing, morphing trailing edge, variable camber, high-lift device, morphing structures, vertical stabilizer, morphing rudder
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Nomenclature

\( c \)  VTP Chord length
\( c' \)  Chord perpendicular to Morphing Starting Line (Non-Morphed geometry)
\( C_l \)  2D Lift Coefficient
\( T \)  Thickness
Glossary

BC  Boundary Condition
CFD  Computational Fluid Dynamics
DISP  Displacement
FEM  Finite Element Method
LC  Lower Camber
LE  Leading Edge
LIP  Load Introduction Point
MPS  Maximum Principle Strain
MSL  Morphing Starting Line
MSP  Morphing Starting Point
NM  Non-Morphed
OP  Optimization Points
SMA  Smart Material Alloy/Shape Memory Alloy
SMP  Smart Material Polymer/Shape Memory Polymer
TDP  Tip Displacement Point
TE  Trailing Edge
UC  Upper Camber
VT  Vertical Tail
VTP  Vertical Tail Plane
1. Introduction / Motivation

“Flying creatures, and especially birds, demonstrate that transit through the air is far more perfect than all others modes of locomotion to be found in the animal kingdom as well as any method of artificial locomotion devised by man…To make this most perfect of all modes of locomotion his own has been the aim of man from the beginning of history. In thousands of ways man has tried to equal the performance of birds. Wings without number have been made, tested, and rejected by mankind, but everything has been in vain and we have not attained this much desired aim.” in (Otto Lilienthal, “Birdflight as The Basis of Aviation”,1911) [1]

1.1 Learning From Nature

For millions of years nature worked improving the birds physiology into an optimal shape adapted to the different environmental and survival demands, allowing different species to fly for long periods of time or perform impressive manoeuvres.

The birds have the exceptional capability of changing the shape of their bodies and wings during the different flight phases and missions: for gliding, hovering, or quickly escaping from predators.

This morphing capability, typical for birds, is important because it influences directly the flow around their body during flight. In cruise, the body and wings morph into an optimum desired shape, reducing drag and maintain altitude with minimum energy consumption. To land safely the bird should reduce the speed, maintaining the same lift. For that, the wings reshape, increasing their camber and consequently providing the needed lift, with reduced flying speed and without stalling. On the other hand, during the last century the aircrafts in general tended to be almost rigid with the minimum moving parts possible to reduce weight, increase the structure stiffness and reduce the failure risk.

Mankind always tried to reproduce the bird flight. Currently for commercial airlines an important parameter is the energy consumption. The fuel consumption per passenger per kilometre has been constantly decreasing, reducing the operating costs, increasing the operational range and creating more environmentally friendly aircrafts.

Usually, the aircrafts in general are designed in a way that could reduce the amount of energy needed for some specific mission segments/design points, typically cruise, and not for all the different known flight phases.

The biologists and engineers studied the bird’s flight and morphing capabilities in detail, inspiring themselves in order to re-shape the aircrafts, improving the efficiency and safety for a wider range of mission segments. The flaps and slats are some examples of adaptive devices that were developed in order to create extra lift/drag, only when it is needed (usually take-off and landing), being retracted in cruise, improving the general efficiency of the aircraft.
Figure 2 shows a Kestrel with the wings and body shaped in different ways, during different flight phases. In Figure 2 the Kestrel Alula, a body member equivalent to the human thumb, can be seen in the front of the bird wing. This part of the body generates vortices in the upper part of the wings, delaying flow separation, allowing smoother and slow landings. In Figure 3 a small vortex generator can be seen in the leading edge of a Cessna 182K with the same function.

This is an example how observing and studying carefully the nature could lead to huge improvements in aircraft performance (see Section 1.3).
It is important to understand that the ultimate objective of morphing devices is to **control the flow around a specific component, in a specific desired way and not to optimize the structure.** The benefit should be measured on an aircraft level and not on the vertical tail itself:

In short, morphing devices typically have the following objectives:

- Optimize the performance of the aircraft in specific flight segments/missions;
- Reduce the noise of the structure by avoiding gaps;
- Increase the controllability of the aircraft with smaller surfaces;
- Drag reduction and fuel saving;
- Improving Vibrations Control

### 1.2 Vertical Tail Plane

An improvement opportunity was identified on a conventional Vertical Tail Plane (VTP) design. The morphing capabilities could theoretically increase the aerodynamic efficiency of this component and consequently reducing the fuel burn and flying cost.

Accordingly, to [2] “Aircraft Design: A Systems Engineering Approach” the Vertical Tail has two main functions in the aircraft:

- **Stability:** After a perturbation the aircraft should have a restoring behaviour stabilising the attitude.
- **Control:** The vertical tail should be able to control the aircraft lateral-directional attitude and movements to perform specific manoeuvres and flight path corrections.

Currently the Directional Stability is mainly provided by the Vertical Stabilizer – Leading Edge (LE) + VT Box - and the Lateral Control by the moving rudder in the trailing edge of the profile (Figure 4). The lateral lift needed to control the aircraft is provided by the rudder deflection in the case of the conventional VTP. The current profile is symmetric as well as the rudder deflection. Usually the rudder is composed by honeycomb plates, actuated by hydraulic systems and rotates about a hinge.

![Figure 4 - Vertical and Horizontal Stabilizer](#)
1.3 Morphing Opportunity

It was identified that the typical Vertical Tail / Rudder configuration leads to some aerodynamic inefficiency, requiring a larger VTP to produce the needed lateral force. This lower efficiency is related to the early induced separation of the flow due to the presence of a sharp corner in the surface. This phenomenon is well known in fluid mechanics and is shown in Figure 5 (Left) as well the potential difference in the flow regime if a round corner is used (right).

The lift generated by the rudder depends in the balance between the right and left side pressure distribution. In Figure 6 the left side curvature doesn’t influence dramatically the flow because the pressure gradient is globally favourable, avoiding separation. On the right surface the separation is induced closely behind the sharp corner and the static pressure quickly increases reducing the suction effect. If the sharp corner present in the current VTP is changed by a smooth curvature corner (as in Figure 5 – right) the separation could be delayed, and the suction effect increased. Globally the lateral forces generated will be higher.

![Figure 5 – Flow behaviour difference in a sharp and round corner](image)

![Figure 6 - Typical separated flow around the conventional rudder (after sharp corner)](image)

This means that a smaller VTP/rudder area would be able to provide the same lift needed to control and stabilize the aircraft laterally. If the VTP size is reduced, the wet area in contact with the exterior flow will decrease, reducing the drag in cruise, comparing to the current configuration. This morphing opportunity depends not in the drag reduction during deflection but in the reduction of the size of the VTP and consequently in the cruise drag reduction.

At least three scientific articles ([3], [4] and [5]) conclude, based on Computational Fluid Dynamics (CFD) calculations and wind tunnel testing, that this technology could lead to real improvements in the aerodynamic efficiency.

Within [4] (page 608) it is referred: “The implementation of those concepts proved to bring a potential increment of 15% on lateral force.” and in [3] (page 12): “These results, point out that the
efficiency of the VTP is improved with the morphed rudder. The lateral force developed by the morphed rudder is 16% higher than the conventional one.

In the article [5] it is stated: "The application of this type of morphing rudder means potential weight savings in commercial transport aircraft empennages, thus representing an important opportunity for aircraft OEMs and Tier 1 suppliers that design and build these types of structures. The more efficient the rudder, the smaller it can be and the less it will weigh. This is an important finding due to the trend in aeronautical research for more efficient aircraft with lower fuel consumption, as well as requirements for reduction of CO2 emissions.

In the following plots from [3] (they were resized to match the axes scale) it is possible to observe a CFD computation result about the surface pressure distribution for a morphing and conventional rudder.

The lift created by a surface like this is proportional to the area between the lower and upper pressure curves. In the lower camber (LC) it is useful to have the highest pressure possible to create positive force and in the upper camber (UC) there should be lower pressure possible to have suction and positive force again (see Figure 6). The curve in the top represents the lower camber and the lower one, the upper camber.

In the morphing graphic (Figure 7 – Left) a larger positive and negative area can be seen when compared to the conventional configuration (Figure 7 – Right). This means that the lift generated by the morphing surface will be higher. The change from the conventional concept to the morphing one should increase particularly the suction/lift generated in the upper camber, because the flow separation is delayed.
Chapter 3 from document [6] refers that after confirming the morphing aerodynamic performance benefit, specifically in terms of fuel consumption, it is necessary to understand the impact and interaction of this with the pre-existent aircraft structure. The most important topics, accordingly to this document, in order to have a technology transition from conceptual design to a real production and flight are:

- Stabilized material and processes
- Producibility: manufacturing scale-up
- Characterized mechanical properties
- Predictability of structural performance
- Supportability

An important requirement about the concept generated within this thesis is to create a system that could be **industrially implemented in maximum 5 years**. For this reason, the aspects listed before should be a priority and constantly checked because they are crucial if the engineers want to turn an idea into a real product.

### 1.4 Thesis chapters description

This document is organized in the same way as the whole research process. The following list gives a short introduction on the different chapter’s topics:

- **Chapter 2 - Morphing Concepts and Technologies** - The different morphing concepts existing nowadays, as well as a trade-off study on the new morphing ideas, are explained in this chapter;
- **Chapter 3 - Target Shape for Morphing** - This chapter presents all the input data used in the FEM analysis and the target shape is defined;
- **Chapter 4 - Morphing Solution** - The way the optimization process and allowables checking is done is explained in detail, as well as a general view on the used kinematic system;
- **Chapter 5 - FEM 2D Strip Model** – This chapter explains how the FEM model was build and the boundary conditions applied;
- **Chapter 6 - FEM Analyses Results** - All the results of the FEM analysis are presented here: shapes comparison, maximum strain location and others. The used allowables are shown here;
- **Chapter 7 - Conclusions and recommendations** - The relevant conclusions on this morphing concept are explained;
- **Chapter 8 - References** - This chapter presents all the used references used in this thesis;
- **Appendices** - All the relevant documents, reference values and tables are shown in this chapter.
2. Morphing Concepts and Technologies

In the following section the state-of-the-art technologies on morphing are described as well as several conceptual designs made. In Section 2.1 a general description is given about the current state of the morphing structures. Advantage and disadvantages are discussed. In the following Section 2.2 a list of possible ways how to morph a structure are given. The list is based upon examples of existing research projects and is extended with other theoretical possible ways to realise a morphing structure. A trade-off analysis is made in Section 2.3 and in Section 2.4 the most favourable concept is selected for further investigation.

2.1 Introduction in STATE-OF-THE-ART Morphing

Several research institutes and companies started working to increase the number of technologies/applications on morphing and increasing the adaptability of structures.

In the beginning some experiments and prototypes were done based on existing technologies with traditional kinematics and materials, creating different wing shape configurations (for example the SARISTU dropping nose or airplanes with variable sweep angle like F-111 and F-14 Tomcat) based on the known technology. Although, there are just a few main market applications of morphing technologies and no implementation in civil aircraft industry.

Several challenges and limitations are related to the known morphing concepts and therefore the industry started searching new materials and ways of deforming the structures.

Usually the cases where morphing is more beneficial (like the change of the wing camber during flight) involves huge displacements between the parts and surfaces of the components. Those displacements can be easily observed when a flap is deployed or when a rudder is deflected (Figure 8). The known solutions involve the creation of a continuous skin that covers the whole system and allow all intermediate deployed/deflected positions, apparently with a reduced number of components.

![Figure 8 – Flap fowler configuration increasing wing camber and aerodynamic morphing profile with equivalent camber](image)

Thus, the structure shape difference between the neutral and target/deformed position in those components will probably induce strains in the structures bigger than the allowables and probably out of the elastic region, in the known materials.
This is not an option within the aerospace industry where the structures are designed to withstand loads inside the linear-elastic region, avoiding plastification, and guaranteeing a safe margin.

For this reason, the academy and industry started to develop materials that could deform more with less induced stresses in the material. This propriety is characteristic from elastic materials like rubber where huge strains can be applied with low internal stress. The stiffness of those materials is low and this creates an engineering paradox: in one side it is requested that the material can withstand high strains and in the other side it should resist to the same loadings without significant deformation as the current aircraft structure.

For this purpose, different technologies, materials and structural designs were created, documented and are available to the academic and industry community.

In addition to the typical aircraft design requirements the following points apply to a morphing design:
- High deformability
- Low induced stresses
- Ability to achieve pre-determined and intermediate shapes
- Stability in both neutral and deformed position
- Higher actuator force-moment density

The biggest challenge is to accomplish these new requirements and respect all the previous ones, especially in terms of weight and safety. Typically, not-mature innovative solutions imply a decrease in safety. This happens due to application of new kinematic driving systems, new unqualified materials and missing in service experience. To improve the maturity level and thus the structure safety, a significant amount of design loops and/or testing is required. This is one of the biggest obstacles to the implementation of morphing on real aircrafts.

This thesis research found that it is important to distinguish several aspects that are somehow mixed in the literature.

Morphing is all about relating different subjects and interaction between different components: the exterior shaped skin, responsible to create desired aerodynamic effects/forces and the actuation, corresponding to the internal kinematics. Traditionally those tasks are performed independently, by different components.

It would be preferred to design components and systems that could perform several functions at the same time, reducing the number of parts and the final weight. It would also be interesting if those new materials and technologies could be mixed in a way that the components could perform double tasks, for example a skin that could be used as an aerodynamic exterior shape and actuator at the same time.

Several materials and technologies were studied and can fit within this objective if combined properly. Some technologies, state-of-art materials and structural designs are briefly explained with some examples for each different technology.
2.2 Examples of Existing Research Projects – Available Technology

2.2.1 Piezoelectricity

This phenomenon is well known nowadays and has great potential in several areas. The piezoelectricity is known from mid-18th century and it is the capacity of materials to accumulate electric charge in response to mechanical stress or in the opposite way.

A piezoelectric actuator (example in Figure 4) is able to impose deformations and deform itself when an electric current is applied. Those materials and actuators are used when a lot of force and a few displacement is needed. The strains induced in the material by the current is relatively small [7] but the force density is really high because of the reduced volume occupied by these actuators. This characteristic may be interesting for some applications but not for others where huge displacements are needed. Some advantages and disadvantages are presented in Table 1.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>◦ High Force Density</td>
<td>◦ Small strains allowed (±0,1%)</td>
</tr>
<tr>
<td>◦ High precision</td>
<td>◦ High cost compared to conventional solutions</td>
</tr>
<tr>
<td>◦ Low actuation time</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 – Advantages and Disadvantages of Piezoelectric Components

• BK117 – Active Flap Rotor

A BK117 helicopter was successfully tested in 2005 by Eurocopter (see Figure 10) using piezoceramic actuators in the blades, for noise reduction purposes with an active flap rotor [7]. Those actuators move the flap in order to create an aerodynamic blade shape change that compensate the vibrational loads.
• F/A-18 Vertical Stabilizer - Active Vibration Control

A group of Canadian researchers developed a solution to reduce the vibrational loads in the high-performance fighter F/A-18 vertical tail based on the usage of improved piezoelectric actuators - Multiple Macro Fibre Composites (MFC) - Figure 11. Several control systems provided a real-time actuation, controlling the vibration modes of the fin, reducing the buffet loads experienced by it and extending the fatigue life of the aircraft [8].

![Figure 11 – F/A Vertical Stabilizer with Active Vibration Control installed](image)

### 2.2.2 Shape Memory Alloys (SMA) and Smart Materials Polymers (SMP)

Shape Memory Alloys (or Smart Material Alloys) and Polymers are a group of materials that have the special ability to change the microscopic molecular configuration depending on the applied temperature path. This microscopic phenomenon has consequences in the macroscopic scale, allowing high strain reversible deformations.

The magnitude of those deformations is typically experienced by metals in the plastic-permanent deformation region. Those materials have also the ability to “memorize” the initial shape and return to it when submitted to a heating process.

Other characteristics that Smart Materials have are numbered in [9] as:

- **Self-actuating**: *The system produces an output such as force, displacement, heat and light after being stimulated.*
- **Self-sensing**: *in response to changes in the environment, the system can generate electric or magnetic signals or undergo strain that can be measured to describe the environment.*
- **Self-Adaptative**: *The system, can change its geometry to adapt to the environment.*

Table 2 shows some advantages and disadvantages of SMA and SMP.
Table 2 – Advantages and Disadvantages of Shape Memory Alloys and Polymers

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Low power needed to actuate</td>
<td>• High actuation time</td>
</tr>
<tr>
<td>• High strains allowed</td>
<td>• Poor fatigue properties</td>
</tr>
<tr>
<td>• Huge research on the topic available</td>
<td>• High cost compared to conventional solutions</td>
</tr>
<tr>
<td></td>
<td>• Continuous energy feeding for deformed position</td>
</tr>
<tr>
<td></td>
<td>• Incompatibility with thermal range of aircraft usage</td>
</tr>
</tbody>
</table>

Some examples of technologies on SMA and SMP are shown below but much more exists. The research on this is huge and it is one of the most promising ones.

**Variable Geometry Jet Nozzle – SMA**

Boeing developed a patent on a variable jet nozzle based on Smart Material Alloys (Nitinol) in order to reduce the noise produced by the secondary flow of a GE115B engine - Figure 12. The actuators contract or expand depending in the temperature of the flow, changing the shape of the nozzle. The devices demonstrated their operationability during 6 flights with 3 engine configurations [10].

![Figure 12 – Boeing 777-300ER equipped with Variable Geometry Jet Nozzle [10]](image-url)
• Variable Camber Wing with Shape Memory Polymer Skin [11]

In this research a skin made out of SMP was manufactured and assembled in the upper camber of an aerodynamic profile in order to camber it - Figure 13. The deflection of the skin under aerodynamic load was measured and correspond to the simulation results [11]. This particular solution is interesting because the skin behaves as an aerodynamic profile and actuator at the same time. This saves a lot of weight in the structure because there is no need of additional systems to morph the neutral shape.

![Composite Corrugated Structure (left) and Shape Memory Polymer Skin (right) [11]](image)

**2.2.3 Skins Elastomers**

Elastomer materials have the special ability to deform more than metals before rupture. In these materials, the elastic region is usually wider, what means that they can be stretched more than others and return to the original shape without permanent deformation.

International Union of Pure and Applied Chemistry (IUPAC) define polymer material as “Polymer that displays rubber-like elasticity”. Thus, theoretically, they are the most fitting ones to the industry demand on adaptive devices because they can be used as a flexible skin, shaping the exterior geometry in the different morphing positions. Several materials exist within this chemical category but just a few can be considered for aerospace purposes. The adaptive trailing edge (ATED) built within the European project SARISTU uses these materials to fill the kinematic gaps and shape the TE exterior geometry.

• Elastomer-Based Skin on SARISTU project [12]

A new morphing skin was designed within the SARISTU project to cover the trailing edge adaptive device based on elastomer materials (see Figure 14 and Figure 15). The skin material was developed with the focus on the low temperature requirements, resistance to environmental conditions and long fatigue life. Several tests were done to select the appropriate material. This material should guarantee the integrity of the device during flight and during the whole life of the aircraft [12].
Currently, there is no reference to a real application of morphing concepts in the Vertical Tail Plane. A lot of opportunities exist in other components, for example the wings, where the morphing capabilities are very relevant. The current configuration of the VTP+Rudder is very simple with a known behaviour, thus is a huge risk to change for design.

### 2.2.4 Active Aeroelastic Aircraft Structures (3AS) and NOVEMOR projects

Huge research concerning new morphing structures was performed within “Active Aeroelastic Aircraft Structures (3AS)” project [14]. A new configuration for the VTP was proposed based on an Active All-Movable Vertical Tail, replacing the conventional one. This research assumes that this technology can lead to a total reduction of the VTP size, lower structure weight, reduced bending moment due to the smaller span and to reduced drag in-cruise.

European project “Novel Air Vehicles Configurations: From Fluttering Wings to Morphing Flight” (NOVEMOR) proposed new morphing solutions for the vertical tail. For example, in the case of a Joined Wing Aircraft Configuration, a study on the Maximum Take Off Weight was performed for different vertical tail sweep angles [15], optimizing the aircraft performance.
2.3 Morphing Concepts Trade-off

The selection of a specific concept on morphing structures is a complex process and dependent on several interconnected variables. In order to select a concept with a high probability of success, an appropriate trade-off analysis should be performed, taking into account the most significant variables.

Several concepts were developed, using different technologies with different levels of maturity, to achieve successful morphing of the Vertical Tail Plane. The objective of these concepts is not to create a detailed engineering description but having a rough idea about what will be the internal structure needed to support the skin, the actuation mechanism and the main structural weak points. With these specific concept proposals, it is possible to compare solutions and select the most promising ones. Figure 18 shows a sketch of the current structural arrangement of the Vertical Tail.

![Figure 18 – Traditional VTP Structure](image)

It is possible to separate the morphing concepts into two major categories depending on the type of skin used to define the external shape of the morphed VTP element. After some detailed study on the kinematic mechanisms available, the known actuators and the different possible combinations it was understood that the skin is one of the most restricting components of the assembly. It was understood that if the skin is made of a non-elastic material the top and the lower surfaces should be disconnected in the trailing edge or in the vertical stabilizer/rudder interface, allowing sliding because the strain/stress level range permitted in the structure is relatively small (around 5000 με –see Appendix D.1).

The following description determines what is considered an elastic and non-elastic material in the context of this thesis:

- **Low Elasticity Modulus Materials**: This type of materials allows high strains with relatively low stress. An example of elastic material is rubber or a silicon elastomer.

- **High Elasticity Modulus Materials**: Those materials usually develop a lot of internal stress when loaded, with low strain. This is the case of a composite or aluminium sheet.

Several concepts using piezoelectric actuators were rejected from the beginning due to the small strains allowed by these actuators. In section 2.2.1 it is explained the main problem related to this technology. The displacements involved in this specific case are completely out of scope considering piezoelectric actuators.
2.3.1 Trade-Off parameters

The following trade-off between the several concepts is based in the assumption that the aerodynamic efficiency will be increased in the same way for all the concepts comparing with the current VTP configuration.

In order to create a trade-off matrix several evaluation parameters were defined:

- Design Maturity / Time to entry into service
- Mechanism / Actuation Simplicity
- Manufacturing Cost
- Maintenance / Operationability
- Damage Tolerance / Reliability
- Weight

A value was attributed to each category, varying between 1 and 5 for the different concepts. In this phase of the design the rating is often qualitative as detail numbers are not available.

2.3.1.1 Design Maturity / Entry into service

This parameter evaluates the time needed to bring a concept into a real commercial flying aircraft. Only well studied ideas, phenomena and concepts could come into service due to the high level of confidence needed in air transportation. Typically, the aircraft industry is conservative and uses established technology rather than change to a completely new one, without extensive research. Components with brand new materials, with unpredicted behaviour, are not desired by the manufacturer for short term applications. The scoring for this parameter is determined as follows:

- Value 1 for a highly visionary concept, using technology far away from being considered safe and useful within a short-term period or using not certificated materials.
- Value 3 for concepts that could be applied in a near future but need more maturation.
- Value 5 for technology that can be used in an aircraft soon due to the low risk and the predicted behaviour expected.

2.3.1.2 Mechanism / Actuation simplicity

Mechanism and actuation simplicity is fundamental in order to achieve high reliable systems. The number of parts and the number of actuators / actuator points are important factors when evaluating the
simplicity of a mechanism. The existence of sliding joints will imply that the tolerances will increase. Thus, additional lubrication is needed during the entire life of the components. Concerning actuation, the electrical and hydraulic systems are the preferred ones. Pneumatic systems are considered not so good because of the difficulties involving air tightness and air leakage identification. Hydraulic systems are considered good because it is easy to find any possible leak and the available force density is high, for example. The scoring for this parameter is determined as follows:

- Value 1 for highly complex systems with a lot of connections, parts and sliding joins. Complex actuation.
- Value 3 for mechanisms with medium complexity.
- Value 5 for very simple, reliable and known mechanisms and actuation principles. Mechanisms with few components are preferred.

### 2.3.1.3 Manufacturing cost

Manufacturing cost is one of the biggest drivers of the aerospace technology/projects nowadays and usually determines if a conceptual project will go into the production line. Great ideas and projects could be rejected if the manufacturing cost is not sufficiently low.

Complex single parts are expensive to produce and the industry typically rejects them. A huge number of parts it is not desired for the same reason. Easy and fast assembly processes should also drive the design process, reducing production cost. Highly restricted tolerances in parts increase a lot the manufacturing cost and additional dimensions checking are needed. Repeated and simple parts are preferred. The scoring for this parameter is determined as follows:

- Value 1 corresponds to a huge manufacturing cost, probably rejected by industry.
- Value 3 corresponds to a usual manufacturing cost.
- Value 5 corresponds to a huge cost saving in parts manufacturing.

### 2.3.1.4 Maintenance / Operationability

An important design principle is to create systems/components that are easy to maintain and operate through the entire life-cycle of the airplane. The use of movable parts needing lubrication (special rollers and sliding parts) should be avoided as well as any other part that requires constant care and attention. The accessibility of the inner part of the system/structure is crucial if there are components requiring maintenance or constant inspection. The assembly and disassembly process should be simple, involving few steps.
The robustness of the parts is important, avoiding the need for excessive maintenance. The chosen concept and system should be easy to repair, and the main future issues/problems should be predicted and expected. The scoring for this parameter is determined as follows:

- Value 1 for a concept and structure involving a lot of maintenance and with few accessibility.
- Value 3 for concepts with intermediate maintenance needed.
- Value 5 to a concept with a few maintenance needed, very simple assembly and operation processes.

### 2.3.1.5 Damage Tolerance

This parameter assesses the ability of a part / assembly to withstand damage, safeguarding the whole structure and the other sub-systems. It is desirable that cracks within an airplane part could take sufficient time to propagate, being detected, before cause a catastrophic failure in the aircraft. This parameter also evaluates the ability of the structure to sustain the loads and guarantee the functionality of the primary systems in the case of part/sub-system failure. The scoring for this parameter is determined as follows:

- Value 1 for concepts with low damage tolerance, high susceptibility of failure and low redundancy.
- Value 3 for concepts with intermediate damage tolerance.
- Value 5 for concepts highly tolerant to damage, controlled crack propagation and with high redundancy.

### 2.3.1.6 Weight

The low weight is one of the most important requirements in the aviation industry since that it is directly related with the power needed to maintain sustained flight and so the amount of burned fuel. The scoring for this parameter is determined as follows:

- Value 1 is reserved for situations where there is a severe increase of weight comparing with the actual system.
- Value 3 is attributed if the concept has a weight similar to the current systems, accomplishing the same functions.
- Value 5 is attributed when there is a huge weight saving with the new concept.
2.3.2 Concepts Description

2.3.2.1 SARISTU Concept / Finger Concept

This morphing concept is based on a finger skeleton structure, with an elastic skin, for the trailing edge. There are linkages between the parts, transmitting the movement and a torque actuator to rotate one of the sections. The elastic skin guarantees the continuity of the upper and lower surface between the rear spar and the trailing edge of the profile in the neutral and deformed positions. This arrangement was used in the European project SARISTU [16], as can be seen in Figure 19 and Figure 20. This kinematic arrangement is typical from robot hands because it accurately simulates the movement of a human finger. More information about this kinematics can be found in [17] and [18]. Table 3 presents the attributed values to different parameters within this concept.

![Figure 19 - Kinematic details from SARISTU Adaptive Trailing Edge (ATED) [16]](image)

![Figure 20 - SARISTU / Finger Concept [12]](image)

<table>
<thead>
<tr>
<th>Trade-off parameter</th>
<th>Attributed Value</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Maturation / Entry into service</td>
<td>2</td>
<td>High-Elasticity materials used with no aerospace certifications</td>
</tr>
<tr>
<td>Mechanism / Actuation Simplicity</td>
<td>5</td>
<td>This Mechanism is very simple and SARISTU project used it</td>
</tr>
<tr>
<td>Manufacturing Cost</td>
<td>3</td>
<td>The cost of this system is probably bigger the current one but this was already done so the costs are predictable</td>
</tr>
<tr>
<td>Maintenance / Operationability</td>
<td>4</td>
<td>This concept is known and a prototype already exists so the needed maintenance can be predicted and inside kinematics easily accessed</td>
</tr>
<tr>
<td>Damage Tolerance/Reliability</td>
<td>3</td>
<td>Several actuators and load introduction points increase redundancy but materials are not certified for extreme situations</td>
</tr>
<tr>
<td>Weight</td>
<td>2</td>
<td>This solution probably involves an increase in the total weight</td>
</tr>
</tbody>
</table>
2.3.2.1 Balloon Concept

This concept consists in an integral morphing vertical tail structure that could generate the lateral force/stability needed, equivalent to the usual configuration VTP+RDR. This is based in the assumption that a small change in the thickness and camber of the VTP profile can increase the lateral lift as much as an actual ruder deflection, with an increase in efficiency. It is assumed that the skin continuity and smoothness along the exterior surface delays separation, ideally increasing lift. Figure 21, Figure 22 and Figure 23 show the evolution of the concept design. Table 4 presents the attributed values to different parameters within this concept.

![Figure 21 – Balloon Concept phase 1](image)

![Figure 22 – Balloon Concept phase 2](image)

![Figure 23 – Balloon Final Concept](image)

<table>
<thead>
<tr>
<th>Trade-off parameter</th>
<th>Attributed Value</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Maturation / Entry into service</td>
<td>1</td>
<td>The aerodynamic efficiency of this solution is not known with highly complex kinematics</td>
</tr>
<tr>
<td>Mechanism / Actuation Simplicity</td>
<td>1</td>
<td>This concept involves a lot of sliding joints</td>
</tr>
<tr>
<td>Manufacturing Cost</td>
<td>1</td>
<td>The cost of this concept is huge because of the increased number of parts and complex kinematics</td>
</tr>
<tr>
<td>Maintenance / Operationability</td>
<td>1</td>
<td>Roller joints need a lot of maintenance. The huge number of parts increases the need of maintenance</td>
</tr>
<tr>
<td>Damage Tolerance/Reliability</td>
<td>2</td>
<td>If a part of this structure is damaged probably this will influence the entire mechanism</td>
</tr>
<tr>
<td>Weight</td>
<td>1</td>
<td>The complex kinematics and huge number of parts will probably increase the total structure weight</td>
</tr>
</tbody>
</table>
2.3.2.2 Crocodile Concept

This morphing concept is based on a finger segmented structure, with a rigid skin for the, trailing edge. The internal mechanism is the same as in the Finger Concept. Once the external skin is made out of a high-stiffness material, for example aluminium or composite, it should slide over the skeleton and be open in the trailing edge tip or near the rear spar.

This concept was created because of the lack of elastic skin material certificated for aeronautical purposes. Thus, certification could be easier due to the vast existent knowledge on aluminium and composite sheets. This specific concept considers that the morphing skins are attached do VTP box near the rear spar and the skin slides in the tip of the trailing edge. This implies a sliding free region between the UC and the LC allowing movement and contact between the surfaces.

Figure 24 and Figure 25 show the same concept with a slightly variation in the sliding device: the first is based on a low friction polymer sliding across the skin and the second on metallic rollers with the same function. Table 5 presents the attributed values to different parameters within this concept.

![Figure 24 - First iteration on Crocodile Concept](image)

![Figure 25 – Final Iteration Crocodile Concept](image)

Table 5 – Crocodile Concept trade-off table

<table>
<thead>
<tr>
<th>Trade-off parameter</th>
<th>Attributed Value</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Maturation / Entry into service</td>
<td>4</td>
<td>The basic technology involved is well known as well the expected behaviour</td>
</tr>
<tr>
<td>Mechanism / Actuation Simplicity</td>
<td>4</td>
<td>This kinematics are similar to SARISTU project with the additional complexity of the rolling joins</td>
</tr>
<tr>
<td>Manufacturing Cost</td>
<td>2</td>
<td>Probably this solution is more expensive than the current one</td>
</tr>
<tr>
<td>Maintenance / Operationability</td>
<td>3</td>
<td>The same as SARISTU Concept but with increased need of maintenance because of the roller joints</td>
</tr>
<tr>
<td>Damage Tolerance/Reliability</td>
<td>2</td>
<td>The damage tolerance of this concept is not known, however several load introduction points and actuators act in parallel</td>
</tr>
<tr>
<td>Weight</td>
<td>2</td>
<td>This solution probably involves an increase in the total weight</td>
</tr>
</tbody>
</table>
2.3.2.3 Worm Concept

This morphing concept is based on a finger skeleton structure, with a non-elastic skin, for the trailing edge. In this concept the chain elements are connected as in the finger concept and have sliding tracks incorporated in the main structure. The chain elements are actuated independently. The low elasticity skin is reinforced with stringers connected to the sliding connections in the chain elements, sliding freely along the sliding joint - Figure 26. Table 6 presents the attributed values to different parameters within this concept.

![Figure 26 – Worm Concept](image)

<table>
<thead>
<tr>
<th>Trade-off parameter</th>
<th>Attributed Value</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Maturation / Entry into service</td>
<td>1</td>
<td>This technology is considered unsafe and highly visionary</td>
</tr>
<tr>
<td>Mechanism / Actuation Simplicity</td>
<td>2</td>
<td>These kinematics are highly and uses a lot of sliding joints</td>
</tr>
<tr>
<td>Manufacturing Cost</td>
<td>1</td>
<td>The costs associated to this concept are unknown</td>
</tr>
<tr>
<td>Maintenance / Operationability</td>
<td>2</td>
<td>Roller joints need a lot of maintenance. The huge number of parts increases the need of maintenance</td>
</tr>
<tr>
<td>Damage Tolerance/Reliability</td>
<td>2</td>
<td>The damage tolerance of this structure is unknown</td>
</tr>
<tr>
<td>Weight</td>
<td>1</td>
<td>The complex kinematics and huge number of parts will probably increase the total structure weight</td>
</tr>
</tbody>
</table>

2.3.2.4 Forced Path Concept

This morphing concept is based on a fixed structure, with a moving high-stiffness skin for the trailing edge. The idea is about using some specific tracks to guide a composite stiffened panel along a pre-defined path correspondent to the minimum energy “bending path”, similar to an “involute” curve - Figure 27. This concept was abandoned at a very preliminary stage because of the huge complexity inherent to the concept and some mechanical impossibilities. Table 7 presents the attributed values to different parameters within this concept.

![Figure 27 - Forced Path Concept](image)
Table 7 – Forced Path Concept trade-off table

<table>
<thead>
<tr>
<th>Trade-off parameter</th>
<th>Attributed Value</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Maturation / Entry into service</td>
<td>1</td>
<td>This concept is highly visionary</td>
</tr>
<tr>
<td>Mechanism / actuation simplicity</td>
<td>1</td>
<td>The needed kinematics for this concept are unknown</td>
</tr>
<tr>
<td>Manufacturing Cost</td>
<td>1</td>
<td>Probably this concept can’t be manufactured</td>
</tr>
<tr>
<td>Maintenance/Operationability</td>
<td>1</td>
<td>The maintenance level needed is unknown</td>
</tr>
<tr>
<td>Damage Tolerance/Reliability</td>
<td>2</td>
<td>The damage tolerance of this solution is unknown</td>
</tr>
<tr>
<td>Weight</td>
<td>2</td>
<td>This solution probably involves an increase in the total weight because more kinematics are needed to actuate the skin</td>
</tr>
</tbody>
</table>

2.3.2.5 SMA Tubes/Sheets Concept

These morphing concepts are based on the use of several SMA actuators actuation independently. Due to the similarity between the Tubes and Sheets concepts, they were merged. In the SMA tubes concept the actuators are connected to a segmented High-Elasticity skin, morphing the trailing edge. An electric system drives the actuators and allowing the heating of the SMA tubes due to Joule Effect (see Figure 28). The tubes will expand and contract independently and the elastic skin would follow the movement. The connection between the elastic segments should be metallic to allow coiling of the tubes and change in global shape.

![Figure 28 – SMA Tubes Concept](image)

In the case of the SMA Sheet Concept the smart material plates shape directly the exterior skin of the trailing edge and drives the system at the same time. An electric system heats the SMA sheets which triggers the material to morph in a different shape. The SMA sheets, connected to different electrical circuits, can be expanded and contracted independently. The cooling process is faster than in the previous concept.
because the SMA element is in direct contact with the exterior flow, increasing the heat flux (see Figure 29). The heating process will cost more energy than usual due the same reason as cooling. Table 8 presents the attributed values to different parameters within this concept.

### Table 8 – SMA Tubes/Sheets Concept trade-off table

<table>
<thead>
<tr>
<th>Trade-off parameter</th>
<th>Attributed Value</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Maturation / Entry into service</td>
<td>1</td>
<td>This concept relies on state-of-art materials, uncertificated for aerospace</td>
</tr>
<tr>
<td>Mechanism / actuation simplicity</td>
<td>3</td>
<td>This concept relies on skin SMA actuation, there is no need of additional actuators</td>
</tr>
<tr>
<td>Manufacturing Cost</td>
<td>1</td>
<td>The cost SMA fabrication with constant behaviour is probably high and the industrial processes unknown</td>
</tr>
<tr>
<td>Maintenance / Operationability</td>
<td>2</td>
<td>The reduced number of parts facilitates the maintenance but this kind of materials deteriorate easily when exposed to extreme conditions</td>
</tr>
<tr>
<td>Damage Tolerance/Reliability</td>
<td>1</td>
<td>If this structure is damaged the actuation system will be highly influenced</td>
</tr>
<tr>
<td>Weight</td>
<td>5</td>
<td>This concept would save a lot of weight comparing to the conventional solution because the skins also behave as an actuator</td>
</tr>
</tbody>
</table>

![Figure 29 – SMA Sheets Concept](image)

### Table 8 – SMA Tubes/Sheets Concept trade-off table

<table>
<thead>
<tr>
<th>Trade-off parameter</th>
<th>Attributed Value</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Maturation / Entry into service</td>
<td>1</td>
<td>This concept relies on state-of-art materials, uncertificated for aerospace</td>
</tr>
<tr>
<td>Mechanism / actuation simplicity</td>
<td>3</td>
<td>This concept relies on skin SMA actuation, there is no need of additional actuators</td>
</tr>
<tr>
<td>Manufacturing Cost</td>
<td>1</td>
<td>The cost SMA fabrication with constant behaviour is probably high and the industrial processes unknown</td>
</tr>
<tr>
<td>Maintenance / Operationability</td>
<td>2</td>
<td>The reduced number of parts facilitates the maintenance but this kind of materials deteriorate easily when exposed to extreme conditions</td>
</tr>
<tr>
<td>Damage Tolerance/Reliability</td>
<td>1</td>
<td>If this structure is damaged the actuation system will be highly influenced</td>
</tr>
<tr>
<td>Weight</td>
<td>5</td>
<td>This concept would save a lot of weight comparing to the conventional solution because the skins also behave as an actuator</td>
</tr>
</tbody>
</table>

#### 2.3.2.6 Duckbill Concept
This concept is based on a composite reinforced skin actuated directly by hydraulic actuators - Figure 30. Other projects used technology like this, confirming that this solution is feasible. The long distance between the load introduction point and Rear Spar generates a structural challenge. On one side the structure should be stiff to withstand the Air loading without excessive deformation and on the other side it should be thin to reduce the actuation force. Table 9 the attributed values to different parameters within this concept.

![Figure 30 – Duckbill Concept](image)

Table 9 – Duckbill Concept trade-off table

<table>
<thead>
<tr>
<th>Trade-off parameter</th>
<th>Attributed Value</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Maturation / Entry into service</td>
<td>2</td>
<td>The technology used is well known but the real behaviour is completely unknown</td>
</tr>
<tr>
<td>Mechanism / actuation simplicity</td>
<td>5</td>
<td>This concept is very simple as well the</td>
</tr>
<tr>
<td>Manufacturing Cost</td>
<td>3</td>
<td>This concept has a cost probably equivalent to the current configuration</td>
</tr>
<tr>
<td>Maintenance / Operationability</td>
<td>5</td>
<td>The maintenance needed in this concept is equivalent to the current configuration and probably very simple</td>
</tr>
<tr>
<td>Damage Tolerance/Reliability</td>
<td>3</td>
<td>The damage tolerance of this kind of structure is not well studied</td>
</tr>
<tr>
<td>Weight</td>
<td>2</td>
<td>The angle of the cylinder load direction is close to 90° to the movement direction of the panel. A high overall drive load is needed making the system and structure heavy</td>
</tr>
</tbody>
</table>

24
2.4 Selection of Morphing Concept - Trade-off results

2.4.1 Relative Weight of the Trade-off Parameters

In this section a relative importance is given to each parameter for the project when evaluating different concepts as can be seen in Table 10. For example, if a concept is good performing the task but doesn’t fit with the low-cost requirement it can be rejected.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Weight Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Maturation / Entry into service</td>
<td>35%</td>
</tr>
<tr>
<td>Mechanism / Actuation Simplicity</td>
<td>10%</td>
</tr>
<tr>
<td>Manufacturing Cost</td>
<td>20%</td>
</tr>
<tr>
<td>Maintenance / Operability</td>
<td>10%</td>
</tr>
<tr>
<td>Damage Tolerance / Reliability</td>
<td>10%</td>
</tr>
<tr>
<td>Weight</td>
<td>15%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
</tr>
</tbody>
</table>

The major criterion during this design research was to find a concept that could be implemented in a short future by AIRBUS with matured concept and technologies. This is the reason why a value of 35 % was attributed.

After this, typically, another driving criterion for new projects within the aerospace industry is cost. The manufacturing cost affects directly the final price of an airplane and should be as low as possible. The Manufacturing Cost value of 20% was defined based on this. Besides direct manufacturing cost several parameter as the total weigh of the structure, damage tolerance/reliability and maintenance / operability are very important because they affect directly the operation cost to the airliners.

The weight of the structure will affect directly several aspects like operating cost. The value of 15% was attributed.

It was considered that, comparing to the categories with a higher trade-off weight, that the other parameters will have a value of 10 %. They are important but less than the previous ones.

The evaluation above results in a specific combination of weights that is considered the important for the analysis in this report. Depending on the goals of the project the balance between the parameters could be different. For example, if the project has later entry into service then the weight of the design maturity would decrease. Resuming, all the attributed values are presented in Table 11.
2.4.2 Results

The output of this trade-off study is the Figure 31, where different concepts can be globally compared against the considered parameters and weights attributed to the different concepts.

![Figure 31 – Trade-off plot comparing different morphing concepts](image)

This table confirms that the crocodile concept is the most promising one, considering the previous explained weights, with the best chance to be into service in a shorter time. The weight of 35% attributed to the "Entry into Service" category combined with a high score attributed to Crocodile Concept in the same one produced these results. SARISTU trailing edge and Duckbill concepts have higher scores concerning several parameters with a reduced weight and, because of that, they get closer to the Crocodile Concept. This concept was selected also because it purposes an innovative solution not studied in detail in the literature.

<table>
<thead>
<tr>
<th>Table 11 - Different concepts with correspondent categories scores</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weight</strong></td>
</tr>
<tr>
<td>Design Maturation / Entry into service</td>
</tr>
<tr>
<td>Mechanism / actuation simplicity</td>
</tr>
<tr>
<td>Manufacturing Cost</td>
</tr>
<tr>
<td>Maintenance/Operationability</td>
</tr>
<tr>
<td>Damage Tolerance/Reliability</td>
</tr>
<tr>
<td>Weight</td>
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</tbody>
</table>
3. Target Shape for Morphing

The morphed shape defined by the exterior skin should be such that improves the efficiency of the VTP and allows a reduction on its size. To improve efficiency a new aerodynamic arrangement should be found in order to get the same lift as the current solution with a smaller vertical tail.

The efficiency improvement opportunity exists because in the actual tail configuration the separation occurs in an early stage, in the interface between the vertical stabilizer and the rudder, decreasing the lift generated by the deflection of the control surface. This effect gets bigger for increased rudder deflection angles.

The morphing technology can be a solution for this issue. Usually, the aerodynamic department should define an optimum shape for this purpose and the structural and systems engineers should design a structure and kinematics that could achieve that aerodynamic shape in the best possible way. This is the methodology used in this thesis, thus the base aerodynamic shape is considered as an input.

3.1 Input Data

3.1.1 AIRBUS Hamburg Project

An initial assessment for an aerodynamic morphed profile was performed by AIRBUS Hamburg, providing some useful input data that could be used in this thesis. The provided data included a preliminary study on the aerodynamic shape for the deformed position of the VTP, as well as some other relevant parameters relating aerodynamics and computational geometry points. This shape was used as the basis for generating new shapes in this thesis.

The aircraft analysed in this study was the AIRBUS A320 once it is the most used aircraft from the refereed company. The analysed profile section was the root section of the A320 VTP as shown in Figure 32.

![Figure 32 – VTP with considered ROOT Section](image)

This shape was considered as a target shape for further structural assessment. Additional research on the optimum shape should be performed in the future, considering the kinematic and skin aspects of a
specific concept. Some qualitative input was given by different aerodynamic departments concerning that
data, describing some important improvement possibilities and some limitations of the input model:

- The conservation of the skin length during the morphing movement is neglected;
- The upper camber geometric points generate a non-uniform shape near the deflection zone;
- The profile Ci could be improved if the radius of the upper camber is increased;

This information was used to improve the base model and create a new one.

### 3.1.2 Separation Point

The Separation Point (SP) considered during this research was based on a simple aerodynamic
calculation in the input profile from the previous section. Only the rough location was made available for this
thesis (in this phase of the design this accuracy is sufficient). The separation point was then extrapolated
all across the 3D surface, defining a flow separation line. This line is used in the VTP Selection Program
surface, generating a Separation line used as a reference for the next analysis.

### 3.1.3 AIRBUS Drawings Database

Useful information was extracted from AIRBUS A320 drawings database [19], as well as the shape
dimensions of the VTP and the current working principles and actuation.

Several manual measurements were done as well as a deep study on the current VTP configuration.
This was important because the new concept should fit perfectly with the existing VTP structure.

The morphing design presented in this thesis considers that the morphing rudder shape in neutral
position coincides with the current A320 honeycomb rudder configuration. It is considered that this shape
should not be changed because it is aerodynamically optimized, especially for non-deflected position.

### 3.1.4 VTP Pressure Distribution

The air load applied to a control surface as the rudder influences directly the structure design. A
structure can behave properly and accomplish the allowables without air loading applied and behave in a
totally different way within a flight situation. This is the reason why air loading should be considered. Other
loads are important for VTP structure design as can be seen in Section Appendix E but in the first analysis
they were neglected. Airbus VTP Loads Specialist provided a 3D air pressure distribution for the entire fin,
corresponding to a reference load case representative of a significant load situation in the current aircraft
configuration (not in the morphed case). This data was provided as an element pressure distribution in a
*Hypermesh* 3D model created within this thesis context, for this purpose.
3.2 **VTP Section Selection Excel® Program**

An Excel® program called "VTP Section Selection" was created to obtain any desired VTP cross-section geometry and other relevant parameters based on the reference data available. The base VTP 3D geometry was extrapolated (Figure 34 – Left) based on the cross-section cut shown in Figure 34 - Right, based on the correspondent drawing [19]. The measurement was done manually and introduced in the program accordingly to the draw scale factor - Figure 33.

This program is crucial because the relevant section for morphing is not the one provided by the drawn section but on a different one, with different slope. With that, it is possible to know where the morphed target points are across the entire surface, from root to tip.

![Figure 33 – Considered Reference Section for VTP Section Program](image)

![Figure 34 - Tapered Extrapolation - VTP Section Selection Program](image)

### 3.2.1 Skin Length Conservation

The initial study performed by AIRBUS in Hamburg used a linear analysis to determine the final morphed shape, not considering the conservation of the skin length during the deflection movement. The computation of the correct dimension was based on the assumption that the Upper Camber (UC) and Lower Camber (LC) skins don’t change length during the entire movement.

In the Excel program created for the new analysis, the total skin length was computed based on the distance between the available morphing points and the new conserved dimension was determined (Figure 35).

![Figure 35 – Excessive skin length computation](image)
The previous graph shows the TE UC surface length correspondent to the linear analysis that shall not be considered. The LC skin conserved length corresponds to the linear case in this specific morphed position. It is also known that the initial aerodynamic shape provided by the aerodynamic department is not directly feasible, not only because of the simplified linear analysis shape determined, but also due to the lack of matching analysis with the kinematics, in this early stage of the design. This matching is discussed in detail in the next chapters and influence the allowed morphed shapes produced.

With the corrected length determined, the best way of putting both UC and LC in contact in the TE tip has to be decided, with a minimum impact in the profile aerodynamic performance. In a first iteration it was considered that the downstream flow after the UC separation point is separated. Thus, the correspondent area is not generating lateral lift properly and the local shape doesn’t affect a lot the performance of the aerodynamic profile. On the other hand, in the LC surface, the flow is attached and influences a lot the generated lift. This LC surface shape was considered in a fixed morphed shape and independent from the upper skin morphed shape (explained in 4.5 - Internal Finger Kinematics - Imposed Displacements).

### 3.2.1.1 Corrected Upper Camber Spline

In order to define the new upper camber skin shape, a drawing spline ruler was built. This type of rulers was really common among aircraft and ship manufacturers to draw smooth splines, passing through some specific desired points, shaping the curves of those vehicles. This technique allows to have a minimum energy shape in the bended material between the fixed points, and a line can be drawn directly (see Figure 36).

In this morphing case of this thesis, the drawn line should take into account the advices numbered in 3.1.1. Thus, the build ruler has the length of the Non-Morphed (NM) Skin. Afterwards, it is forced (with a bending moment applied in the tip) to have a bigger radius near the Rear Spar (RS) and touch slightly (with a vertical imposed displacement applied) in the Lower Camber skin (Figure 37).

After drawing the line, all the previous points were relocated manually into the Excel Program. Some corrections in the TE point were done to have the exact length of the Non-Morphed Skin.
The initial morphed shape points were relocated (see relocated curve in Figure 38) and an Excel® 5th order polynomial spline (this was the polynomial line that fitted better) was created based on them, in order to obtain a smooth curvature and the correspondent polynomial equation. This new line can be observed in Figure 39.

![Figure 38 – Manual Spline Correction](image)

![Figure 39 – Final UC 5th order spline shape](image)

### 3.2.2 Morphing Starting Line Location

After having this new corrected aerodynamic profile, it is important to define the last point (downstream) connected to the rear VTP spar, where all degrees of freedom are constrained (fixed constrain). This point was called as Morphing Starting Point (MSP), where the bending starts. The group of MSP from the root until the VTP tip is called Morphing Starting Line (MSL). This point can be defined on different chordwise positions (Figure 40).

![Figure 40 – Possible locations for a Morphing Starting Line (just for visual reference)](image)
The geometric final shape obtained in the 3D Vertical Tail depends a lot in several kinematic and load-dependent parameters (like VTP bending). The 2D strip model used can’t predict those effects and considers that the final shape is the same for all the cross sections. The twisting due to curvature radius variation spanwise can’t be predicted with this program. It was considered that, to avoid excessive twisting in the real VTP, the **Morphing Starting Line should be tapered as the whole structure and the morphing movement should happen in a plane perpendicular to it.** This guarantees that the aerodynamic shape is constant spanwise, maintaining the geometry proportion, from root to tip (see Figure 41).

This means that both X and Z distance (see Appendix A.1) between two consecutive points in the profile shape vary linearly spanwise but the global shape remains the same. This was assumed both in the 2D and in the 3D VTP FEM Models. If the rudder is morphed in a different direction than the perpendicular one, the proportion of the aerodynamic shape will probably change spanwise and torsional non-desired effects can happen.

Future studies could research about any additional benefits from having a different angle between the morphing direction and the morphing starting line.

After having a full surface coordinates model of the VTP (both in Non-Morphed and Morphed condition) it is possible to test several different MSL’s. The model built allows different chord percentage for the MSL position and checks, in the perpendicular plane, what is the exact starting point (MSP). Assuming

![Figure 41 – Morphing Perpendicular to Morphing Starting Line](image)

![Figure 42 – Reference Shapes for Morphed and Non-Morphed configurations in a random section](image)
that the skin will bend perpendicularly to this line, it is desirable to define this point it in the correspondent bending plane. The following Figure 42 shows a random section selected based on an arbitrary starting line between Rear Spar and 100% chord length. The plot starts in the Rear Spar of the VTP. There are several points that could be used to fix the skin. Several criteria are relevant during this selection:

- The MSP should be in the region where the Non-Morphed and the Morphed shape coincides, allowing the movement;
- The morphing starting point should not be really close to the RS to leave some space to the rudder assembly and to create enough attachment surface area to the skin;
- In order to reduce the bending stresses, for a specific deformation, the MSP should be as close to RS as possible. This will imply a bigger curvature of the skin reducing the bending stresses within “bending only” shape;

It is important to remember that the shape geometry to be analysed is dependent on the MSL chosen because the VTP cut slope will vary with that. Thus, it is mandatory to select a MSP prior to any type of analysis. Based on the previous criteria a value of 65% of the chord length was chosen for the Morphing Starting Point/Line. This point is far enough from the RS (allowing attachment and maintenance – in the VTP tip the margin is around 200 mm – space needed to insert a human hand) and far enough from the region that should move (Trailing edge TIP). This is just a first iteration and other MSL can be analysed in the future. Figure 43 shows an arbitrary section perpendicular to the 65% chord line with the Morphing Starting Point selected.
4. Morphing Solution

4.1 Optimization Methodology

The design of an entire morphing VTP involves a lot of different interconnected subjects, thus, some initial simplifications were done to reduce the number of variables and allow a fastest system initial analysis.

The final objective of the research is to find an optimum location of the load introduction points (LIP) fixing the skin to the kinematics (Figure 44) and spanwise thickness distribution, ensuring the following characteristics:

- Correct geometric desired morphed shape;
- Stresses and strains are below the material stress/strain allowables;
- The skin waviness generated by the air load is within an allowed range;
- The structure has stability under air loading;
- Low actuation force needed to move and to maintain deformed position;
- Light structure;
- The structure has a good damage tolerance.

4.1.1 Strip Model

In order to simplify this complex 3D optimization problem, the chordwise and spanwise effects/deformations were decoupled and an initial chordwise strip model was selected for further assessments. The general optimization methodology is described in Figure 45.

This research is focused in the Strip Model phase and the results could be used as an input in the future 3D Model.

A strip model is often used to simplify complex 3D models and reduce the amount of variables. Useful information can be extracted from these models and used as an input in more complex analysis.
Strip Model Assumptions:
- No variations of properties and geometry in spanwise direction;
- No 3D flow effects are considered;
- 3D Tail Bending is neglected;

Within this research, the following variables were considered: thickness and the distance between successive load introduction points. These variables are driving the stresses, strains and displacements experienced by the skin. Those effects will probably perform a major role during morphism and could impose limits and boundaries in the allowed morphed shape. The mechanical effects explained before can be named as Bending Stiffness and Air Load Waviness. Figure 46 represents the expected behaviour of a morphed skin strip under air load.

![Figure 46 – General behaviour of the skin strip under known loads](image)

The Bending Stiffness problem is related with the force than needs to be applied just for bend the skin until the final desired morphed geometry.

The Air Load Waviness problem is related to the existence of a gap between successive Load Introduction Points where no internal structure exists counterweighting the exterior pressure. This bulging displacement will induce additional strain/stress in the structure and should not be bigger than a prescribed displacement allowable. This bulging may also influence the aerodynamic flow if it gets too big.

To have a first estimation on the relative weight of the different variables, small deformation equations (extracted from [20]) can be used and manipulated:

\[ \delta_B = \frac{PL^3}{3EI} \leftrightarrow P = \frac{3\delta_B EI}{L_1^3} \]  
\[ \delta_{\text{max}} = \frac{5qL_2^4}{384EI} \]  
\[ L_1 = \text{distance between fixed support and tip} \]  
\[ L_2 = \text{distance between supports} \]  
\[ I_x = \frac{bh^3}{12} \]  
\[ h = \text{thickness} = t \]  

![Figure 47 – Reference for Equation Parameters [18]](image)
• **Bending Stiffness** – Using Cantilever equation with tip load (1) and (3)

\[
P = \frac{\delta_{BE} b}{4} \times \frac{t^3}{L_1^3}
\]  

(4)

• **Air Load Waviness** – Using two sides supported beam with distributed load equations (2) and (3)

\[
\delta_{max} = \frac{5q}{32 Eb} \times \frac{L_2^4}{t^3}
\]  

(5)

We typically want to **avoid too much waviness, reduce the stress and strain within the structure and reduce the force needed to bend the skin**.

Analysing the previous Equation (4) it can be concluded that, for the force needed to bend (morph) the rudder into an extended position, both thickness and distance have the same relevance. For the air load waviness/bulging (Equation (5)) the distance is more relevant than the thickness.

If both equations are considered during the design phase an engineering paradox needs to be solved: if the thickness is reduced to decrease the bending force (Equation 4), the waviness displacement will increase (Equation 5). In the opposite way if the thickness is increased to reduce the waviness displacement the bending force will increase, accordingly to the same equations. The waviness can also be reduced by applying more load introduction points, reducing the distance between consecutive supports. Thus, a compromise between number and position of LIP as well the skin spanwise thickness distribution should be found.

Considering this simplification, the number of spanwise LIP lines (represented by green lines in Figure 48) is **constant all over the VTP**. This is important because after defining the number of LIP lines and distance between them, thickness is the only parameter that could vary spanwise.

Because of the tapered geometry considered, the distances between LIP lines in the VT tip will be proportional to distances in the root section and vary linearly spanwise (Figure 44). As the geometry proportion is constant spanwise the radius of the morphed skin will decrease from the root to the VT tip (Figure 49) as well as the distance between LIP lines.

Thus, the worst Bending Stiffness issues will be located in the VT tip for a constant spanwise thickness. The worst air load waviness issues will be more relevant in the root section where the distance between LIP it is the biggest.
Because of the boundary values of bending stiffness located in the VTP tip and air load bulging in the VTP root it was decided to analyse both the lowest and the highest sections of the morphing rudder (perpendicular to the MSL) represented in Figure 50.

Two strip FEM models were made based on the geometric data extracted from the Excel® Program VTP Section Selection. It is assumed that the strains, stresses and displacements between these two sections will be in between the extreme values and vary linearly from the VTP root to tip.

To reduce the initial amount of variables in this parametric optimization problem the number of LIP Lines should be defined for the first analysis.

If only one bending point is used, only "minimum energy bending shapes" can be achieved. Those shapes are formed when a beam or plate is bended between 2 points. If additional bending points are introduced the energy stored in the beam will increase, increasing the material stress.

Figure 51 shows the comparison between a minimum energy shape and the target one, for an arbitrary thickness with a vertical bending displacement applied in the shown point, without considering the applied air load.
Considering the target shape as the most optimized in terms of aerodynamic efficiency, the minimum energy shapes, with one bending point, will never coincide with this one. The target shape consists in a more complex spline, only achievable with more bending points.

If the displacement point is moved upstream the trailing edge may not have enough stiffness to maintain the desired shape in flight. Thus, a bigger stiffness reinforcement is needed to avoid excessive tip displacement when air load is applied.

As a second criterion, it is assumed that reducing the number of load introduction points it is usually good and saves weight in the whole structure.

Because of this the following iteration uses 2 LIP, allowing more morphing shapes with a better fitting to the target curve. The TE point shown in Figure 51 is maintained in a fixed skin location and an additional displacement point location varied between the MSL and the Tip Displacement point.

Thus, the number and position of the load introduction points should be applied to the strip models and evaluated both in the root and tip of the VTP as referred in Section 4.1.1 and shown Figure 50.

### 4.1.2 TIP Displacement Point Location

In order to avoid excessive air load bending in the trailing edge of the morphed rudder, a LIP should be placed as close as possible to it. This point can have different locations dependently on the stiffness solution used in the sliding tip and the internal kinematics. It is not reasonable and real to consider a displacement applied by kinematics in the trailing edge tip of the selected section because it would be overlaid by the other sliding surface and therefore there is no space to attach a kinematic/stiffener element. Thus, a first guess in the location of this point should be done in order to perform further analysis.

This point should be placed over a tapered line (as the MSL) at a constant chord percentage. Thus, the most constraining area in terms of space for actuator and kinematics will be the VTP tip where the space in between skins is smaller.

Two main parameters were considered to define this point:

- In the correspondent VTP tip section there should be enough space to place kinematics;
- In the correspondent VTP root section the distance between this point and the trailing edge tip should be as short as possible to increase the bending stiffness of the TE.

Analysing both sections and the real dimensions it was defined that this point should be placed in a position of approximately 90% of the VTP chord length. This position guarantees a distance between skins of 60 mm, necessary to install future kinematics, in the TIP section. In the perpendicular plane to the MSL those points correspond to approximately 88% of the chord (see convention in Appendix A.2).
If the distance left between skins is not sufficient the kinematics may need to be shifted to a lower VTP section where more space is available and new FEM Analysis should be performed. Figure 52 shows the tip shapes, the Tip Displacement Point (TDP) and other relevant points specified.

![Figure 52 – TIP Section perpendicular to MSL](image)

### 4.1.3 Optimization Procedure

After defining all the fixed parameters that are independent of any optimization process (in this case the MSL - Morphing Starting Point and the TDP - Tip Displacement Point) a specific methodology should be defined to achieve the desired goals.

The input variables are (as explained in Section 4.1.1) **the thickness of the plate** (see thicknesses in Section Thicknesses and Material Considered) and the **location of the second LIP** (see the different locations in Section 4.3), **both for Tip and Root Sections** and the output should be checked against several criteria and allowables. There are these two parameters and multiple goals, thus it is not possible to optimize to a unique design point. Instead of that it was decided to create a matrix of points for the two variables. The resultant matrix will be evaluated against the defined goals.

Figure 53 shows the Allowables Checking Procedure both for VTP Tip and Root:

![Figure 53 – General Optimization Process Description](image)
4.2 Thicknesses and Material Considered

During an engineering design process, selecting the appropriate material to accomplish the desired function is an important step. Typically, aluminium skins are easy to manufacture, the material behaviour is well known, and a lot of experience exists within the industry. However, the fatigue needs to be considered, especially if a part is loaded cyclically with high strains/stresses, as the morphing rudder. Composites have good fatigue properties, are also certificated for several aeronautical applications and the manufacturing techniques are established. After this first simplified assessment it was defined that the material used in this morphing concept would be a carbon fibre composite layup. The available thickness of the layup depends on the available manufacturing techniques, commercialized raw material (plies). Therefore, the total layup thicknesses will be only obtainable in discrete steps.

In this case for the optimization a set of specific layups and thicknesses are defined in the beginning of the analysis. To obtain those composites, with a constant behaviour not depending a lot in the layup, several stacks were designed accordingly to the rules presented in Appendix F. Figure 102 (see Appendix B) shows clearly that, for the “bending only” case, the strains within the composite skin increase linearly - the points are aligned - in all LIP configurations. This proves that all the composite layups designed for this thesis present an equivalent global linear behaviour, not depending in the layup. This is important because the analysis and optimization result will not be influenced by the internal composite stack and a global composite behaviour can be considered, depending only in thickness.

Composite layups and total thicknesses used in the analysis (shown in detail in Appendix F):

- A - 2,000 mm
- B - 2,540 mm
- C - 3,048 mm
- D - 4,064 mm
- E - 5,080 mm
- F - 6,096 mm

4.3 2nd Load Introduction Point Location

The Displacement constrains locations was varied accordingly to the following table, represented in Figure 54:

- Point 0: Over Morphing Starting Point
- Point 1: \( x' = 0,6415 \ c' \)
- Point 2: \( x' = 0,7011 \ c' \)
- Point 3: \( x' = 0,7650 \ c' \)
- Point 4: \( x' = 0,8146 \ c' \)

For reference: \( Tip \ c' \approx 1,8 \ m \quad Root \ c' \approx 4,3 \ m \)
During morphing movement, the points in the surface move both in vertical and horizontal direction. Thus, the initial and final positions should be known. In the previous linear analysis study this wasn’t done and only the vertical position of the skin points changed.

The VTP Section Selection program is innovative because it allows the exact calculation of the initial and final position of a skin surface point for the different VTP sections. In the FEM analysis the imposed displacements should be inputted in the Non-Morphed Position considering the final position to be achieved. Figure 55 shows the different locations of a random surface point when the morphing surface is in neutral position or fully deflected. A random point between the RS and the Trailing Edge can be selected with this program and their morphed and non-morphed coordinates found.
4.5 Internal Finger Kinematics - Imposed Displacements

It is important to understand the local interaction between a general kinematic system and skin because some model inaccuracies and future design incompatibilities can be avoided. For this reason, a first preliminary study was done to understand if this type of kinematics could achieve the desired shape.

The internal kinematics considered for this design are based on Figure 57. They are important to understand how the displacements are imposed in the FEM Strip Models. These kinematics weren’t studied in detail because the focus of this study is on the skin panels. The concept was split into skin and kinematics, as shown in Figure 58. After that, it was decided that only the top skin/upper camber would be studied because it is the one we want to optimize, in terms of aerodynamic shape.

Figure 56 shows an example of a specific combination of 3 kinematic ribs. The red dots in the kinematic surface tells where the rollers should be to achieve the desired target shape. The orange dots correspond to the load introduction points in the skin where the rollers are attached.

Concluding, a finite number of kinematic rotation ribs, with specific rotating ratios relation and dimensions can achieve a desired shape from this type. Further research should be performed to understand better the interaction between the lower camber and the kinematics.
Typically, the kinematic system imposes a specific displacement in the structure, developing a **reaction force in the structure as a consequence**.

In this concept (see Figure 59) the kinematics deformed position imposes not a vertical displacement but a sloped one, defined by the sloped surface of the kinematic “finger” parts. This is the same of saying that the reaction force will have only a component normal to those surfaces.

It was decided to **impose only vertical displacements** (Figure 60) in this model, trying to simulate the sloped ones, in the points being analysed based on the following procedure:

- Select a Morphed Surface point to move and check the correspondent one in the non-morphed position;
- Check the initial and final coordinates of this node;
- Determine the correspondent Z (vertical) displacement and apply it to the structure - Figure 61.

This assumption introduces some model inaccuracies including a premature instability phenomenon as can be seen in Figure 62, when air load is applied to the structure. It is known that, when a load is applied to thin unstiffened wall structures, they can become unstable. In this case it is expected the same behaviour, however, this specific vertical displacement modelling makes the UC Skin much more sensitive. If the plate thickness is not sufficient to counteract, some air loadings can push the skin away from the target position, making the FEM model analysis diverge.

As shown in Figure 62 there is no horizontal reaction force that could compensate the horizontal component of the pressure vectors. In addition, the pressure applied in the surface “follows” the skin during
bending non-linear iterations, always perpendicular to the surface. Thus, the horizontal pressure contribution will constantly increase, moving the skin into a non-desired unstable shape. This problem is more visible within low thickness sections.

In the real configuration (Figure 59), with sloped supports, this problem is not so important because there is a vertical and horizontal reaction in the kinematic points counteracting the pressure in a better way.

It can be concluded that the results from the analysis in this thesis are conservative because if the skin remains stable within the current model, probably it will be stable in the real configuration. For this reason, the parameter combinations that resulted in unstable behaviour were considered as a “no go situation” even if they could be safely achieved with the real configuration.

Figure 62 – Skin Instability under Air Loading
5. FEM 2D Strip Model

The FEM software used in this master thesis are the **Hypermesh** for pre-processing, **Optistruct** as a solver and **Hyperview** for post-processing. Those softwares are made by **Altair® Hyperworks®**.

The geometry considered for the FEM analysis is based on the **VTP Section Selection Excel®** program, starts in the VTP Rear Spar Point and follows the Non-Morphed Spline (see Figure 63) shape determined before for the Tip and Root Model. The **Smooth Line** tool available on Hypermesh was used to create a spline connecting those points.

![Figure 63 – Morphed and Non-morphed shapes](image)

The 2D strip model should be representative of a section unaffected by the 3D phenomenon. This is the same of considering an infinite section with constant shape size. For this purpose, it is important to define the correct strip width.

During the first analysis it was concluded that, in the case of a composite skin design, **the boundary effects experienced are relevant** due to the complex extremity stress distribution inside the composite layup. To solve this issue the FEM strip model built considered a large width (≈ the same magnitude as the rudder chord length) in order to extract a centred slice section, not influenced by the free side effects. The nodal displacements were applied to a reference configuration and the Composite Maximum Principle Strain and Nodal Reaction Force checked visually. The test proofed that a constant value of those different mechanical parameters is observed. Thus, no further iterations are needed. Figure 65, Figure 64 and Figure 66 show the final shape considered in the tip and in the root, using the thicker layup considered (6,096 mm) where the stronger boundary effects phenomena are expected.
The final widths considered are:
- Root Section - 600 mm width - 40 mm width in the centre analysed slice
- Tip Section - 600 mm width - 20 mm width in the centre analysed slice

5.1 Mesh

The 2D mesh was created automatically by *Hypermesh* using the tool *2D Auto Mesh*. In order to have perfect square shape elements in sufficient number, the side length of each element was defined with **10 mm in the tip** and **20 mm in the root** – see Figure 67.

Composite elements (PCOMP in Optistruct®) were used in this analysis. This element considers a tape layup, symmetric in this case, with individual ply thickness orientation. It is composed by four boundary nodes. Failure criteria weren’t considered in the element properties definition.
5.2 Boundary Conditions

The exact interface between the morphing skin and the wing box wasn’t studied in detail so a first approximation is done. It is considered that the morphing movement starts in the Morphing Starting Line at 65% of the VTP chord. The absolute values used were determined based on the VTP Section Selection Excel® program datasheet, build for this purpose.

Due to the fixed mesh distribution considered, all the boundary conditions were placed in the nearest nodes to the coordinates provided by the VTP Section Selection Excel®.

Two main lines are constrained in all cases: the line close to the RS of the skin and at the MSL point (Figure 68). These nodes had all 6 degrees of freedom fixed. The VTP box is considered to be very stiff compared to the morphing rudder, thus this fixture is a good approximation within an early design phase.

The region in between these supports should be attached to the VTP box over the entire length but this wasn’t simulated in order to reduce the amount of BC – this region exists only for visualization purposes.

![Figure 68 – Rear Spar and Morphing Starting Line Fixed Supports](image)

5.3 Applied Displacements

Accordingly to the procedure described in Section 4.5, the correspondent Vertical Displacements are applied in the correspondent nodes. The nodes selected are the closer ones to the target numerical value, extracted from the Excel® Program.

The applied values are, for each different 2\(^{nd}\) LIP location, the ones numbered below:

- **ROOT:**
  - Point 0 → \(\Delta z = 0,0 \, mm\)
  - Point 1 → \(\Delta z = -4,4 \, mm\)
  - Point 2 → \(\Delta z = -32,9 \, mm\)
  - Point 3 → \(\Delta z = -114,6 \, mm\)
  - Point 4 → \(\Delta z = -212,1 \, mm\)

- **TIP:**
  - Point 0 → \(\Delta z = 0,0 \, mm\)
  - Point 1 → \(\Delta z = -1,4 \, mm\)
  - Point 2 → \(\Delta z = -13,3 \, mm\)
  - Point 3 → \(\Delta z = -48,3 \, mm\)
  - Point 4 → \(\Delta z = -90,2 \, mm\)
5.4 Analysis Type and Parameters

Due to the geometric non-linearity of this problem a linear static analysis will not be sufficient accurate predicting the skin shape after morphing deflection.

Typically, with a linear analysis, the displacement of a beam tip can be neglected. However, in this case, the majority of the skin points will have a considerable displacement both in vertical and horizontal directions. Thus, a linear static analysis would produce very inaccurate results and a non-linear one is preferred. Therefore, a non-linear approach was selected.

The analysis type defined in this case was a **Non-linear quasi-static Analysis** from Optistruct (Altair®) Library with the parameters shown in Figure 69 (the blank spaces are filled with default values from the solver).

5.5 Pressure Distribution

The Air Loads used as input in this thesis were based in a 3D real flow data for the whole VTP. Usually, 2D strip models consider that the airflow is bi-dimensional and the pressure doesn’t vary spanwise. Thus, the needed pressure distribution should be extracted from the 3D model.

For this purpose, it was searched all across the VTP surface a region where the air load would have the biggest magnitude. If such a load case is used, the optimization process will be conservative and the structure will withstand with lower air loadings. With a line pressure distribution, it was created a parametric Hypermesh® field that was applied to both 2D TIP and ROOT Strip models – Figure 70 and Figure 71. This parametric field scales the region where the pressure is applied, maintaining constant their amplitude.
6. FEM Analyses Results

With the analyses performed, there is a better understanding of the behaviour of a bended composite skin, in different conditions. Those analysis help identifying the parameters influencing a morphing design like this and can be used as simplified way of getting in touch with composite non-linear performance, for these morphing purposes. In Section 6.1 the allowables used during the design phase are explained. The description of the results referring the root and tip strip models are shown in Section 6.2 and 6.3, respectively.

6.1 Allowables Checking

The different Optimization Points (OP) considered should be checked against the different allowables and requirements defined for a flying structure like this morphing rudder. The checked parameters are:

- Stability
- Maximum Composite Principal Strain
- Maximum Skin Waviness Amplitude and Slope due to Air Loading
- Deviation from the target shape

The general analysis procedure was done in the following 2 steps path (see Figure 72):

- Step A - Consider the skin just with enforced displacements (“bending only”) and compare the obtained shape with target one. In this step it will be evaluated if any specific optimization point is good achieving the target morphed shape. The reference used to measure the distance is the Target Shape.
- Step B – The Air Load is added to the already bended skin and the deviation between this new shape and the previous one is evaluated. Basically, this step measures the influence of the Air Load in the skin geometry and strains within the material. The reference used to measure the distance is the “Bending only” Shape.

Figure 72 – Reference for displacement evaluation between shapes
The final objective of this analysis is to fill a Requirement Fulfilment Table in order to find the accepted area, with several allowed Optimization Points (Thickness-LIP location combination), respecting the company allowables. The filling process is not the optimization itself. The optimization should be done after the “accepted” points are identified, considering additional criteria as the final structure weight, for example. However, it sets the boundaries of the design within which the optimisation should take place. Table 12 will be the template used during this assessment.

<table>
<thead>
<tr>
<th>TIP</th>
<th>Thickness</th>
<th>A - 2.000 mm</th>
<th>B - 2.540 mm</th>
<th>C - 3.048 mm</th>
<th>D - 4.064 mm</th>
<th>E - 5.080 mm</th>
<th>F - 6.096 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>DISP Point</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**6.1.1 LIP / Maximum Strain location**

One of the outputs of this thesis is a better understanding and prediction about the location of the skin region with the highest induced strain. For simplification purposes and to avoid excessive amount off strain plots a fast-visual checking process is performed.

The intend of this analysis is to prove that, considering a specific LIP, varying the Layup Thickness doesn’t affect a lot the Maximum Principal Strain location in the composite skin. If this is confirmed only one strain plot, corresponding to an arbitrary thickness, needs to be shown, explaining the global behaviour for the other thicknesses, for each LIP.

Figure 73 and Figure 74 show that, for the “Only Bending” and “Bending+Air Load” cases, the location of the Maximum Principal Strain remains almost the same, independently of the thickness considered.

**Figure 73 - ROOT Section - LIP 2 for different Layup thicknesses (D, E and F) – Bending + Air Load**

**Figure 74 - TIP Section - LIP 2 for different Layup thicknesses (B, D and F) – Only Bending**
Considering that the Maximum Principle Stress location will not vary a lot for the other layups, it can be observed in Figure 101 that is possible to check the evolution of the maximum principle strain (MPS) position in the composite for the laminate D (4,064 mm thickness) when the LIP moves between position 0 and 4 in the VTP ROOT and TIP.

Layup D was selected for this comparison because it has an intermediate thickness between the available ones and it is always convergent for all LIP locations.

The top pictures in Figure 101 show the “bending only” cases and the lower one, the cases with this air loading applied in the surface. The left dark blue region represents the area fixed to the VTP box and the rigid TE tip is not displayed because it is not loaded (it should appear in the right side).

### 6.2 ROOT

In the root section, the distance between LIP is the highest so the bending force needed will probably be the lowest in the whole VTP. In the other hand, the biggest VTP air load waviness is expected in this region for the same reason.

#### 6.2.1 Deviation from Target Shape

Figure 75 shows the target shape and all the “bending only” shapes, considering different LIP. It can be observed that, in general, when the LIP moves downstream, the obtained shape get closer to the target shape.

![Figure 75- General view of morphing rudder deflected for different load introduction points (Root)](image)
Figure 76 shows the distance between the target shape and the obtained curves (perpendicularly to the first one). It can be seen the chord percentage where separation is expected, marked with a vertical line.

![Figure 76 - Deviation from target shape (Root)](image1)

Figure 77 shows the same shapes and displacements as the previous ones but within a more detailed view between MSP and SP.

![Figure 77- Detailed deflection view between Morphing Starting Line and Separation Point (Root)](image2)

Since no further aerodynamic analysis was performed for the different obtained shapes and considering that the target shape is the most efficient one, a simple evaluation plot (Figure 78) was done based on some assumptions:
- Only the region between the MSP and Separation point is considered and influences the aerodynamic efficiency;
- The difference between the obtained and target shapes should be minimum - The total positive and negative areas between the displacement curve and the x axis should be minimized (the negatives areas are added as positive);

![Figure 78 – Area below displacement curve (Root)](image)

Considering the assumptions explained before, LIP 2, 3 and 4 would be equivalent and the preferred ones because they correspond to the minimum areas. However, LIP 3 has a small advantage when compared to the other ones.

### 6.2.2 Stability - Skin Strain vs Thickness

The blue points in the left graphics from Figure 101 (Appendix B) represent the “Bending + Air Load” strains correspondent to different thickness for each LIP location. It can be seen that some points are on the X axis or don’t have a linear correlation with the other points. Those points correspond to an unstable skin configuration.

The criteria used to confirm the convergence/stability of the result were:
- The Optistruct analysis should converge after finite time (the points are not on the X axis);
- The strain points should be aligned and have a linear trend.

In Figure 79 it can be observed that, when the thickness increases the difference between the strain before and after, the air loading is reduced and the skin tends to stabilize. Thus, for the root, when the thickness grows, the air loads contribution for the strain is less important and the bending stiffness plays the major role. It is possible to measure the difference between the cases “Bending only” and “Bending + Air Load”. That Strain Relative Difference vs Composite Thickness is shown below for the different LIP locations, for the cases where the analysis is convergent (see error formula in Section Appendix B):
After this analysis all the ROOT Optimization Points using the Composite Layups A, B and C can be rejected because of the instability behaviour under air loading (see Table 13).

### 6.2.3 Maximum Strain Allowable

To check if the Strain Allowable is accomplished it is important to verify what is the loading case that induces the larger strains in the structure. In this case the strains correspondent to the "Bending only Shape" were used because they are (only for convergent situations) the largest ones compared to the "Bending + Air Loads". This is interesting because, in this case, the air loading reduces the strains within the structure. The Figure 80 shows the Maximum Principle Strain for the various LIP locations in relation with the different thicknesses. The red line indicates the allowable (= 5000 µε – see Appendix D.1).

It is obvious that all the Optimization Points considered in the ROOT don’t overcome the Strain allowable. This shows that the root doesn’t have problems with strain at all and more freedom and...
Optimization Points will be available in a future design. Concerning this category, no points should be represented in the Requirement Fulfilment table.

### 6.2.4 Maximum Skin Waviness Amplitude and Slope due to Air Loading

AIRBUS has some criteria to evaluate which level of surface waviness can exist in the final assembled structure. These allowables can vary per structure and per aircraft type, depending on the aerodynamic needs. Currently, there are no allowables available for a morphing rudder.

The selected allowable provide a general trend but needs to be reassessed in case of a more detailed morphing rudder. For this study they are the following values: Max Waviness Amplitude < 2 mm and Max Mean Slope < 0.005 (see Appendix D.2).

This evaluation supposes that a design reference shape exists and compares the final real structure shape with this one. In this case the reference shape used was the shape from situation A (see Figure 72) just with enforced displacements applied.

It was considered that, in this conceptual phase, only Air Loads can generate waviness (manufacturing imperfections were neglected) so the loaded skin shape should be compared to the “bending only” shape and not to the aerodynamic target one. The evaluation about the similarity between the bended shape and the target shape is done separately.

In Figure 81 it can be seen, for each LIP location, the final deformed geometry for the different composite thicknesses and the displacement between the “bending only” shape – “bending + air load”. This distance between curves is measured perpendicularly to the correspondent reference shape.

In this case all the curves have a maximum waviness amplitude larger than 2 mm so they are rejected. Because of this there is no need of checking the slope.
In this case (Figure 82) all the curves have a maximum waviness amplitude larger than 2 mm so they are rejected. Because of there is no need of checking the slope.

In this case (Figure 83) all the curves have a maximum waviness amplitude larger than 2 mm so they are rejected. Because of there is no need of checking the slope.
Within LIP 3 only layup F – 6,096 mm has an amplitude lower than 2 mm. The correspondent F Maximum Slope is below 0.005 so only this LIP-T combination is valid - Figure 84.

Within LIP 4 layups D – 4, 064 mm, E – 5,080 mm and F – 6,096 mm have an amplitude lower than 2 mm. However, the Maximum Slope is below 0.005 only in with Layups E – 5,080 mm and F – 6,096 mm - Figure 85.
6.3 **TIP**

6.3.1 **Deviation from Target Shape**

Figure 86 shows the target shape and all the “bending only” shapes, considering different LIP for the tip section. It can be observed that, in general, when the LIP moves downstream, the obtained shape get closer to the target shape.

![Deviation from Target Shape - Just Bending (Tip)](image)

**Figure 86 - General view of morphing rudder deflected for different load introduction points (Tip)**

Figure 87 shows the distance between the target shape and the obtained curves (perpendicularly to the first one). It can be seen with a vertical line, the chord percentage where separation is expected.

![Deviation from target shape (Tip)](image)

**Figure 87 – Deviation from target shape (Tip)**
Figure 88 show the same shapes and displacements as the previous ones but within a more detailed view between MSP and SP.

Since no further aerodynamic analysis was performed for the different obtained shapes, and considering that the target shape it's the most efficient one, a simple evaluation plot (Figure 89) was done based on some assumptions:

- Only the region between the MSP and Separation point is considered and influences the aerodynamic efficiency;
- The difference between the obtained and target shapes should be minimum - The total positive and negative areas between the displacement curve and the x axis should be minimized (the negatives areas are added as positive).
Considering the assumptions explained before, Points 2, 3 and 4 would be equivalent and the preferred ones because they correspond to the minimum areas. However, LIP 3 has a small advantage when compared to the other ones.

### 6.3.2 Stability - Skin Strain vs Thickness

The blue points in the left graphics from Figure 101 (Appendix B) represent the “Bending + Air Load” strains correspondent to different thickness for each LIP location.

In the case of the TIP strip analysis *Optistruct* solution converged after finite time for all the cases. For this reason, all the strain points are linearly correlated.

It is interesting to observe that the maximum strain difference between the bending and bending+ air load cases is almost constant and null (expect in the thinner skins). This means that, for the Tip, the major contribution for the maximum principle strain is the bending stiffness and the strain due to Air Load can be almost neglected, especially within higher thicknesses. In this case there is no unstable behaviour of the skin.

It is possible to measure the difference between the cases “Bending only” and “Bending + Air Load”. That Strain Relative Error vs Composite Thickness is shown in Figure 90 the different LIP locations when the analysis is convergent (see error formula in Section Appendix B):

![Figure 90 - Strain Relative Error vs Composite Layup Thickness - TIP](image)

After this analysis it is confirmed that all the TIP Optimization Points will always be stable independently of the used Layup/Thickness.

### 6.3.3 Maximum Strain Allowable

In this case, the strains correspondent to the “Bending only Shape” were used because they are the larger ones compared to the “Bending+Aero” Loads, in most cases. Figure 91 - TIP – Composite Maximum Principle Strain vs Load Introduction Point Location for the available thicknesses shows the Strain-LIP
location relation for all the different thicknesses with the red line from the allowable (= 5000 \( \mu \varepsilon \) – see Appendix D.1).

In Figure 91 it is clear that several Optimization Points are outside the acceptable region in terms of Composite Maximum Principle Strain. Concerning this category, Layups E – 5,080 mm and F – 6,096 mm should be rejected in the Requirement Fulfilment table (see Table 14).

### 6.3.4 Maximum Skin Waviness Amplitude and Slope due to Air Loading

The criterion about this allowable category is explained in Section 6.2.4 (page 55) – ROOT Section.
The curve correspondent to layup A – 2 mm is not shown in the right plot (Figure 92) for better visualization purposes. The Maximum Amplitude and Slope weren’t analysed because Point 0 was rejected in the TIP analysis. This concept only works if an Optimization Point is accepted both in TIP and ROOT analysis.

Within LIP 1 (Figure 93), the Maximum Amplitude and Slope weren’t analysed because Point 1 was rejected in the TIP analysis. This concept only works if an Optimization Point is accepted both in TIP and ROOT analysis.

Within LIP 2 (Figure 94), The Maximum Amplitude and Slope weren’t analysed because Point 2 was rejected in the TIP analysis. This concept only works if an Optimization Point is accepted both in TIP and ROOT analysis.
In this case curves correspondent to the composite layups E – 5,08 mm and F -6,096 mm are not considered because they were rejected in the Strain allowables checking. Curve correspondent to layup A – 2 mm is rejected because they have a maximum mean slope larger than 0.005. Curves B –2,54 mm, C – 3,048 mm and D – 4,064 mm are accepted because they respect both the Amplitude and Slope allowables.

In this case the curves correspondent to the composite layups E – 5,08 mm and F -6,096 mm are not considered because they were rejected in the Strain allowables checking. Curves A – 2 mm, B - 2,54 mm, C – 3,048 mm and D – 4,064 mm are accepted because they respect both the Amplitude and Slope allowables.
6.4 Requirement Fulfilment Tables

Table 13 and Table 14 and resume all the previous data. With that it is possible to observe a region where the allowables are accomplished. Those combinations can be used in a further optimization process.

Table 13 - ROOT Requirement Fulfilment Table

<table>
<thead>
<tr>
<th>DISP Point</th>
<th>Thickness</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Instable</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>Instable</td>
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<td>A</td>
<td>A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Instable</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Instable</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Instable</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 14 - TIP Requirement Fulfilment Table

<table>
<thead>
<tr>
<th>DISP Point</th>
<th>Thickness</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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<tr>
<td>0</td>
<td>Strain Not Allowed</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Strain Not Allowed</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Strain Not Allowed</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Strain Not Allowed</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Strain Not Allowed</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.5 Morphing FINAL VTP Shape

Accordingly to the previous Requirement Fulfilment Tables (Table 13 and Table 14) and the design requirement stating that the LIP chordwise location should coincides in both TIP and ROOT sections, some combinations are available and are shown in Table 15:

Table 15 - Allowed LIP – Thicknesses Combinations

<table>
<thead>
<tr>
<th>ROOT</th>
<th>TIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIP 3</td>
<td>LAYUP F (6,096 mm)</td>
</tr>
<tr>
<td></td>
<td>LAYUP B (2,540 mm)</td>
</tr>
<tr>
<td></td>
<td>LAYUP C (3,048 mm)</td>
</tr>
<tr>
<td></td>
<td>LAYUP D (4,064 mm)</td>
</tr>
<tr>
<td>LIP 4</td>
<td>LAYUP E (5,080 mm)</td>
</tr>
<tr>
<td></td>
<td>LAYUP A (2,000mm)</td>
</tr>
<tr>
<td></td>
<td>LAYUP B (2,540 mm)</td>
</tr>
<tr>
<td></td>
<td>LAYUP C (3,048 mm)</td>
</tr>
<tr>
<td></td>
<td>LAYUP D (4,064 mm)</td>
</tr>
<tr>
<td></td>
<td>LAYUP F (6,096 mm)</td>
</tr>
<tr>
<td></td>
<td>LAYUP A (2,000mm)</td>
</tr>
<tr>
<td></td>
<td>LAYUP B (2,540 mm)</td>
</tr>
<tr>
<td></td>
<td>LAYUP C (3,048 mm)</td>
</tr>
<tr>
<td></td>
<td>LAYUP D (4,064 mm)</td>
</tr>
</tbody>
</table>

The conclusion from analysing Figure 78 and Figure 89 (referring to the area below the deviation curve) is that LIP 3, 4 and 5 are very similar in terms of proximity between the “bending only” shape and the target one. A small advantage to point 3 can be observed.

Further, in Table 15, the lower thickness allowed corresponds to the skin design using LIP 4 instead of LIP 3. It is assumed that the structure with the thinner layup will be the lightest one.

With the available information and considering that LIP 4 shape can achieve successfully the aerodynamic target, the lightest structure accomplishing the objectives will have the configuration shown in Table 16

Table 16 – Final VTP LIP-Thicknesses Combinations

<table>
<thead>
<tr>
<th>ROOT</th>
<th>TIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIP 4</td>
<td>LAYUP E (5,080 mm)</td>
</tr>
<tr>
<td></td>
<td>LAYUP A (2,000mm)</td>
</tr>
</tbody>
</table>

Maybe other combinations can be found if other criteria were used to select regions in the Requirement Fulfilment tables. This combination guarantees that the stresses/strains within the composite are below the allowables, the skin remains stable under air load, the waviness allowables are respected and a minimum structural weight achieved (within the considered assumptions and criteria).

During the next comparison it was assumed that the thickness will vary linearly spanwise, between the Root and VTP Tip, considering the previous thicknesses determined, in the correspondent sections.
The final morphing skin weight calculation is based on the computation of the total volume of the upper and lower skins considering several skin segments, approximated as truncated rectangular pyramid sections. This method was used in all the available segments provided by VTP Section Selection Excel® program and the total volume determined, for the red area (Figure 97 – Left). The volume of each red skin strip was based on the division of the main solid in 7 different parts (Figure 97 – Centre). The average composite density used for the weight estimation can be found in Appendix D and it is equal to 1.58 g/cm³.

The total skin weight estimation, between the VTP Rear Spar and Trailing Edge is 96 Kg, including both upper and lower camber skins.

Presentation [21] from AIRBUS defines a target weight for the morphing panels in this configuration of 70 Kg. As it is not a real component weight, this value can only be used as a reference for further comparisons in this project. The main assumptions consist in not considering the load introduction parts because they will be needed even within the new morphing concept.

The weight saving is not linear correlated to the rudder efficiency. However, [21] provides a rough estimation on the total VTP weight saving, if the efficiency is globally increased in 15%. For +/- 5% this is linearly extrapolated, accepting a minor inaccuracy. It is assumed that a horizontal cut in the current geometry in the VTP Tip can reduce the total weight, not affecting the global aerodynamic performance. In both cases the extra weight needed due to the new kinematic system within this morphing concept is not considered in this preliminary study.

<table>
<thead>
<tr>
<th>Reference</th>
<th>( W_{\text{Panels}} ) (Kg)</th>
<th>( \Delta W_{\text{Panels}} ) (Kg)</th>
<th>( \Delta W_{\text{VTP}} ) (Kg)</th>
<th>Total ( \Delta W_{\text{VTP}} ) (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morphing Rudder</td>
<td>+10% 96</td>
<td>+26</td>
<td>-30</td>
<td>-4</td>
</tr>
<tr>
<td></td>
<td>+15% 96</td>
<td>+26</td>
<td>-45</td>
<td>-19</td>
</tr>
<tr>
<td></td>
<td>+20% 96</td>
<td>+26</td>
<td>-60</td>
<td>-34</td>
</tr>
</tbody>
</table>

Table 17 – Final Weight Comparison Table
7. Conclusions and recommendations

Aircraft industry faces new challenges with the increasing importance of environmental issues and the demand for low fuel consumption rates, both because of regulation and airliners claims. Some inefficiency was identified in the AIRBUS A320 Vertical Tail and morphing structures appeared as a possible solution that would ultimately reduce the total fuel consumption rate in flight.

The first objective of this thesis was to search for technologies and solutions that could achieve this aim within five years period. It was concluded that only a few materials and solutions can respond properly to this issue and provide a working system, accomplishing the requirements, in short time. A system based on a bended composite skin actuated by an internal “finger” kinematics design was selected because of its maturity due a strong research in the field, namely within SARISTU European project.

The following aim of this thesis was to check if a composite bended skin system could be shaped in such a way that main allowables (strain or waviness) are respected and a target aerodynamic morphed shape could be achieved. For that, specific combinations of thicknesses and load introduction points were analysed, trying to accomplish those requirements and optimizing the structure, reducing the total skin weight needed. A 2D modelling method was selected to do this evaluation of the skin behaviour in two extreme vertical tail sections: Tip and Root. Those positions were identified as the most relevant ones, where the consequences of the aerodynamic loading (root) and mechanical bending (tip) would be the highest. The FE analyses confirmed that the previous assumption was correct. An allowed design “window” was defined, and a minimum weight optimization process performed.

7.1 Conclusions

It was concluded that it is possible to design a morphing rudder with a short-term entry into service. To achieve this, existing certificated/qualified materials and technologies were selected: a composite stack for the exterior skin and a known “finger” configuration for the internal kinematics.

This research concluded that the optimum thickness should be different in the different extreme VTP sections (Root and Tip) and a skin thickness variation should be considered spanwise to accomplish the relevant allowables and to minimize the weight.

It was determined that, on 2D models considered, the “bending only” shape depend solely on the Load Introduction Points locations and not on the layup thickness. Furthermore, the analysis showed that an optimized aerodynamic shape can only be achieved with a minimum amount of two load introduction points. The chordwise position of those two points in the skin influences a lot the obtained shape. The best combination of skin thicknesses and Load Introduction Points was selected within the allowed ones confirming that, considering the skin point of view, this concept is feasible.

It was concluded that the morphing rudder skin can globally save 19 Kg in the VTP due to the reduction in the size of the structure.

This research proves that bended composite plates can be used as morphing skin, accomplishing all the requirements and allowables.


7.2 Future Recommendations

After this research work it is possible to identify several topics that need further investigation in the future, to understand better this morphing concept and how it can be built.

First, additional research in the base aerodynamic profile shape should be performed to find the most optimized shape that would produce the lateral lift needed. This evaluation could be done in a full-scale model in order to determine the 3D Flow effects originated by this new morphing shape. In parallel, it is important to have a detailed look at the kinematic structure, to get a better overall view on the total design since there is a huge interaction between the different components in this specific concept. A detailed look on the lower camber skin behaviour should be done.

This research could be useful as a base study for the skin, even if different kinematic systems are considered, achieving the same shape, skin strains and displacements. The amount of load introduction points spanwise should be analysed in detail as well the stiffness needed in this direction.

An iterative process is required to match the kinematics with the morphing skin. The morphing shape obtained by specific kinematic systems usually can’t fit perfectly with the target curve, so an aerodynamic assessment is needed to confirm if the obtained shape can create the original desired benefit.

Full rudder FEM analysis is necessary to assess the 3D structural effects and deformations, like twisting. It is important to understand if different Morphing Starting Lines could improve the structural behaviour, reducing stresses or twisting effects. This would also allow a more accurate weight estimation for the full rudder. A thickness variation in the chordwise direction could be researched to evaluate the improvement in the total weight. The air loading due to the 3D effects should be used in further assessments.

Further review in the laminate lay-ups should be performed in order to have the best mechanical properties possible in each different VTP section, considering the relevant local phenomena.

Because of the relative movement between upper and lower camber of the morphing rudder, a solution should be found to cover the tip and root extremities, avoiding structural gaps and excessive noise.
8. References


Appendices

Appendix A  Conventions Definition

Appendix A.1  General VTP Conventions

Figure 98 - General VTP axis considered

Figure 99 – General VTP Aero parameters definition
Appendix A.2  Chord Length Definition

Two main chord definitions are used in this thesis: when a specific point is selected in the surface it can be referenced to the section perpendicular to the MSL or to the global horizontal section of the VTP.

All the distances were converted into dimensionless quantities, dividing them by the correspondent total non-morphed profile length.

\[ c = \frac{\text{Non – morphed surface point distance} \rightarrow x}{\text{total non – morphed chord}} \]  \hspace{1cm} (6)

\[ c' = \frac{\text{Non – morphed surface point distance} \rightarrow x' (\text{perp. to MSL})}{\text{total non – morphed chord (perp. to MSL)}} \]  \hspace{1cm} (7)

Figure 100 – Relation between VTP chord and chord perpendicular to Morphing Starting Line
Appendix B  Relevant Figures

Figure 101 – Strain vs Thickness Plots for Different Optimization Points – TIP(Left) and ROOT(Right)
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Figure 102 – Maximum Principle Strains for different Optimization Points
Appendix C  Relevant Formulas

\[ \text{strain relative difference} = \frac{\varepsilon_{\text{just bending}} - \varepsilon_{\text{bending+air load}}}{\varepsilon_{\text{just bending}}} \] (8)

Appendix D  AIRBUS Allowables and Parameters

Typically, each aircraft manufacturer defines the allowable values to the different mechanical parameters for materials that are part of the load carrying structure.

The mechanical properties and material allowables considered in this analysis were defined by AIRBUS INDUSTRIE based on experimental testing and are described in the company materials documentation.

- Epoxy Prepreg Carbon Fibre

Accordingly to the material documentation sheet [22] the following relevant values can be found for composite plies from Epoxy Prepreg Carbon Fibre UD.

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Appendix D.1  Maximum Strain Allowable

From document [23]:

Table D.1 – Composite Strain Allowable

| Cut-off allowable ($\mu \varepsilon$) | 5000 |

Appendix D.2  Overall Profile & Waviness Requirements

Figure 103 – Waviness convention and parameters
Appendix E  Vertical Tail Loads

This Appendix raises awareness about other important loads and topics that should be considered during a Vertical Tail Morphing Design in the future, providing some important references.

Appendix E.1  Function of Structural Components

The literature explains the main function of the structural components in an aircraft and lists the main loads considered: “The basic function of an aircraft structure are to transmit and resist the applied loads and to provide an aerodynamic shape and protects passengers, payload, systems….This is typically done by a thin shell structure supported by longitudinal stiffening members and transverse frames to enable it to resist bending compressive and torsional loads” [24]-Chapter “Structural Components of Aircraft”

Accordingly to [24] there are several factors that the primary aircraft structure must satisfy:

• Limit Load – maximum load that the aircraft is expected to experience in normal operation
• Proof Load – Product between limit load and proof factor(1.0-1.25)
• Ultimate Load – product of the limit load and the ultimate factor (usually 1.5)

“The aircraft structure must withstand the proof load without detrimental distortion and should not fail until the ultimate load has been achieved” [24]-Chapter “Airworthiness”

Appendix E.2  Dynamic Loading

It is crucial to understand what is the highest load experienced by the vertical tail during the aircraft life, in the worst case operational scenario. It is known that the tail experiences several load configurations during each specific manoeuvres, for example, One-Engine-Inoperative flight.

Document [25] (page 4) refers that: “The magnitude of the load resulting from an instantaneous deflection of the rudder is considerably greater than the magnitude in the final steady state, which corresponds to static conditions.”. In this specific configuration, concerning a flying boat it is stated: “…when dynamic effects are considered, an instantaneous deflection of approximately 15º is necessary in order to reach the ultimate design load obtained from current specifications; whereas when only the static conditions are considered, a rudder deflection of 33º would be necessary to reach this value.”
In [26], dynamic effect that should be considered in the VTP design are listed and explained:

“The rudder deflection induces loads on the fin as well as the rudder. However the primary loading on the vertical tail is caused by resulting side slip angle when the rudder is deflected. The side slip angle can be determined from directional stability.”

As stated in [27] the basic conditions that will determine the maximum loads for the vertical tail and related structures are:

• Yawing manoeuvre conditions (pilot induced and engine out)
• Lateral gust conditions

Appendix F    Composite Layup Design

Quasi-isotropic Layups:
• The same number of plies in each direction. This is difficult to achieve because if you want to increase slowly the thickness you should add just some plies in some specific directions not enabling QI layups.

Some requirements:
1. Typically only 0º/±45º/90º are allowed
2. The exterior layers orientation should be -45 or +45 degrees to avoid delamination during the creation of holes;
3. The 0º plies should be placed in the best spot to allow or avoid bending (in the centre to reduce bending stiffness and in the exterior surface to increase bending stiffness);
4. Two consecutive layers should have a maximum deviation angle of 45º;
5. There should be at least 1 ply in each direction, especially in thin layups;
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Figure 104 - Composite different used layups

Figure 105 - Composite different used layups