Design Modifications of a UAV Wing for Optimal Integration of a Magnetic Anomaly Detection Sensor

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Abstract

This work describes the conceptual design of a Unmanned Air Vehicle (UAV) wing with a Magnetic Anomaly Detection (MAD) sensor for submarine detection operations. Nowadays, underwater marine vessels are able to evade conventional detection methods such as sonar. Therefore, it is necessary to integrate MAD sensors in modern Anti-Submarine Warfare theatres. UAVs typically generate a magnetic field due to the electrical systems on board, causing interference noise on the MAD sensor data analysis and compromising its performance. To address these issues, a characterization of the aircrafts magnetic signature was conducted, and it was found that the wing tip and a tail stinger boom are the best options to minimize the magnetic noise. A structural and aerodynamic analysis of the aircraft showed the wing tip configuration was the best option since the amount of mass required to counter the moment of a tail stinger boom would require major modifications on the UAV. Also, the aircraft magnetic signature is minimum at the wing tip, with an intensity of -2.9nT. An aerodynamic characterization of the aircraft was carried to evaluate the effect of the MAD pods on the wingtips. A parametric optimization of the wing was conducted. Given the dimensional constraints on the wing structure and a target magnetic noise of 2nT at the wing tip, the optimizer objective function was to minimize the total fuel consumption. The optimum solution allowed a decrease of 30% on the magnetic noise and a fuel consumption of 5.77kg of fuel for an 8-hour search operation.

Keywords: Aircraft Design, Unmanned Aerial Vehicle, Anti-Submarine Warfare, Magnetic Anomaly Detection sensor, Parametric Optimization

1. Introduction

Modern ASW is a fusion of technology and tactics [1]. Technology advances allowed submarines to be incredibly quiet while travelling underwater. In the last century, the noise level generated by an underwater vessel decreased over decades, as can be observed in Figure 1.

![Figure 1: Sound signature level evolution comparison between vessels from USA and Russia, in the past century][2]

The sonar is still the the primary sensor on submarine detection but nowadays, they can stay underwater for longer periods, hiding using the environmental surroundings, making their detection as hard as they can. Therefore, a study on the integration of a MAD sensor on a UAV was conducted.

1.1. Aircraft Characterization

The NEBULA N1 was the aircraft chosen to accomplish the proposed mission. This vehicle is an unmanned aircraft developed by NEBULA Unmanned Aerial Systems. It is a modular high-wing monoplane, with a tractor propeller and high T-tail, fabricated using composite materials.

At the time this research was conducted, the N1’s propulsion system was electric, requiring a pneumatic launcher, as displayed in Figure 2, and landing via belly touchdown, which required a smooth field to not compromise the aircraft structural integrity.

The reduced volume of ferromagnetic materials in the airframe was one of the reasons to choose this aircraft for the project, as well as its versatility. Designed to have a modular tractor propulsion system,
this aircraft can be modified into several propulsive configurations, with an electric or a combustion engine. Also, any of the previous configuration can be coupled with 2 electric motors on each wing, giving it VTOL capabilities.

1.2. Sensor Description: MAD-XR

The MAD-XR (Magnetic Anomaly Detection - Extended Role) is a newest generation sensor developed by CAE Inc. With an huge advantage of being compact, this military-grade MAD sensor has reduced weight and size, and its power requirements allows it to be incorporated in a smaller aircraft, such as UAVs [4].

Although not constant, the range of this MAD system will generally detect anomalies at approximately 1200 metres [4], which is crucial factor to determine the flight altitude.

1.3. Project Requirements

A) Magnetic Signature

To maximize the sensors performance, it must be placed such the amount of magnetic interference generated by the aircraft is minimized.

B) System Constraints

As discussed in section 1.2, the MAD-XR is composed by two components: the sensor itself and an interface unit, responsible for the data logging and analysis. According to the manufacturer, the distance between these devices must not exceed 2.5m.

The interface’s mass is approximately 650 grams and the harnessing between this unit and the MSU weighs, approximately, 200 grams per meter.

C) Flight Operations

In a patrol operation, the goal is cover the maximum area as possible to increase the chances of success. Typically, these types of mission are characterized by a target loiter time over a designated search area, away from the take-off point. For this project, the performance and operational goals were the following:

1. Vertical take-off from a ship over the ocean;
2. Cruise for 20 nautical miles at 50 m/s;
3. Perform patrol/search mission for 4 to 8 hours, at 40 m/s;
4. Dash back in same conditions as item 2;
5. Vertical landing at the initial point.

In figure 4 is possible to visualize the mission, according to the list displayed above.

Depending on the aircraft performance and aerodynamics, the cruise and loiter altitudes may differ. Due to the conceptual nature of this study, an equal altitude of 300ft (approximately 100m) for these stages was considered. This value allows the aircraft to fly as low as possible without compromising its own safety. Also, submerged targets could be at a significant depth, thus lower altitudes always provide better chance of target detection.

To achieve these objectives, the N1 will be modified towards an hybrid propulsion configuration, having a combustion engine and fixed-pylon electric motors as sources of thrust, as shown in fig 5. The VTOL system will be used only for take-off, landing and the transition phases between these and horizontal flight. In cruise and loiter stages, it would be shut-downed, making the N1 perform like a conventional fixed-wing aircraft.

2. MAD-XR Location Assessment

2.1. Magnetic Signature

Hansen [1] characterized the magnetic properties of the aircraft, measuring the intensity of the magnetic field of each component in the field using magnetometers and making computational analysis with COMSOL, a finite element software.
According his analysis [1], the main sources are enumerated, as follows, in order of significance: propulsive units (combustion engine, VTOL motors, ext), servos/actuators (flight control, gas throttle), assorted avionics and ferromagnetic fasteners, as shown in figure ??.

To respond to this issue, many configurations were considered, based on another aircraft and similar studies. However, due to the nature of the project and objectives, some of them were discarded because of their unfeasibility, in terms of aerodynamics, sensor’s efficiency or overall structure.

Therefore, only conventional fixed-wing MAD configurations were considered, in which the options were a wingtip placement or a “stinger boom” at the tail.

3. Weights & Balance
This study was conducted in both electrical and gas configuration, regarding the difference of both propulsive systems. Although not crucial for the final product, it was important to carry out this analysis because most of the initial flight test would be conducted using the electric mode. As so, it was important to verify if the best solution suited with both configurations.

The final assessment was carried out using an Excel flight stability tool, developed by the aircraft’s designer, used for flight test stability checking. As a convention, the referential for the components coordinates has its origin on the intersection of the wing’s leading edge and the aircraft symmetry plane, as displayed in figure 7. Z-axis is perpendicular, in the opposite direction to the readers’ sight.

From previous operations, all base configuration components, such as the airframe and propulsion system, were already characterized and their position on the aircraft was correctly specified.

As highlighted earlier, adding a mass to an aircraft is a procedure that requires cautiousness, because it will have consequences on the performance and aerodynamics of the aircraft. According to N1 designer [3], there were two main parameters to take into account in this process:

1. The maximum take-off weight (MTOW) could not exceed 35 kg;
2. To keep the aircraft’ stability, the x-position of its center of gravity (CG) should be kept between 0.140m and 0.146m.

From [3], it was known the N1’s mean aerodynamic chord (c) is 0.2649m and the aircraft neutral point is at \(x = 0.179\)m, so during the process, the objective was to keep the CG’s position at \(x = 0.143\)m.

Knowing the sensor’s mass is about 1.5kg, it was assumed the wrapping pod and mounting frame were going to be prototyped in a 3D printer and would have, approximately, 0.5kg of mass. At this point, the wire’s weight was not considered to equilibrium calculations.

From this point, for nomenclature simplification, when referring to the MSU’s mass, it will accounted its own (1.5kg) and the container (0.5kg), totalling 2kg for analysis.

3.1. Configuration Analysis
3.1.1 Tail Stinger Boom
In this configuration, adding a mass to the aircraft will induce a large nose-up pitching moment, equal to the product of MSU’s weight and distance to the aircraft’s CG, as shown in the following equation

\[
M_{MSU} = (x_{MSU} - x_{CG}) \times W_{MSU} = l_{MSU} \times W_{MSU}
\]

where \(l_{MSU}\) was equal to 1.71m, defined according to Hansen’s analysis [1].

One condition to achieve steady level flight is that the sum of moments about the CG has to be null. Adding a single to the aircraft will induce a pitching moment, except if placed on the CG, which was not an option. Therefore, it was necessary to account for integration of a second mass, to cancel the MSU’s moment and keep the aircraft stable when flying.
To minimize the amount of mass to be added and achieve the same moment, it was required to get the highest arm as possible. Therefore, it was decided to locate the CW next to engine mount, occupying voids in the structure, distanced 0.57m to aircraft’s CG. Due to the small volume availability, it was thought to use led, profiting its high density.

Figure 8: Acting loads from MSU and respective counter-weight

To compute the CW’s mass, it was only necessary to apply equilibrium of moments about the CG, using the diagram in Figure 8:

\[ W_{MSU} \times l_{MSU} = W_{CW} \times l_{CW} \]  \hspace{1cm} (2)

3.1.2 Wing Tip Configuration

For this case, the calculations were much easier, since both wingtips were going to be modified to keep the aircraft symmetry. Therefore, no additional lateral trimming was required, if the added mass on each wing was the same. Once again, led was used as counterweight for the MSU.

3.2. Weight Assessment

Having established the governing equations to the problem, it became simple to accurately compare these configurations. In this section, an evaluation of the amount of mass required to trim the aircraft is made for each propulsive configuration. Although not crucial for the final goal, it was important to evaluate the aircraft in electric-mode since all the initial flight testing were conducted on that configuration. The objective was just to assess if the same solution suited both propulsive configurations: electric and combustion.

The airframe weighs 14.45kg, which will be added 1kg due to the MAD-XR interface unit (MIU) and respective harnessing. This measurement was conducted when the aircraft was configured to electric propulsion, so it includes the electric engine.

3.2.1 Electric Propulsion

When on this configuration, N1 the electrical engine power is supplied from a battery, weighing 4.45kg \[3\]. On the moments analysis, it was included in the aircraft’s weight, given the fact their position was already known, totalling 19.9kg for the airframe.

Figure 9 represents the results of the computations.

As expected, the mass of the counter-weight has a direct consequence to the aircraft’s payload capacity. For the electric configuration, the tail stinger boom requires more than twice the mass of CW required for the wing tip. This chart suggests the wing tip solution has a more benefits than the other, regarding the total added mass. However, as explained earlier, the electric mode is only used for flight testing and to decide which option should be applied it was necessary to evaluate the combustion configuration.

3.2.2 Combustion Engine

For this assessment, it was required to remove the components of the electric engine and install the combustion system.

From measurements, it was concluded the electric and gas system weigh 1.6kg and 5kg, respectively. For the latter, the position of the fuel tank was not already defined, although was intended to place it onboard the fuselage, coincident to the aircraft’s CG. Therefore, the fuel was accounted as payload and airframe’s mass equal to 18.8kg.

Figure 10: Comparison of the mass distribution of each option for the gas engine configuration

Similarly to the electric mode results, the wing tip solution is best one, since the total added mass
is approximately half the added on the tail stinger boom.

3.2.3 Additional Aspects

From the operational point of view, there were some aspects to be considered. According to the N1’s designer [3], the aircraft is able to fly more than 3 hours per kilogram of fuel, at cruise speed, reason to choose a solution that provides the highest payload possible. Also, each configuration studied had some benefits and disadvantages. The tail stinger boom has a high risk of damage due to ground reaction on landing and requires longer manufacturing time. The wing tip is easier to produce, improves the aerodynamic efficiency because wing tip pods would work like a winglet [5]. However, it would require special maintenance and installation procedures due the fact some components are thicker than the wing at some points.

3.3. Result Discussion

Comparing the results from Figures 9 and 10 and list of additional aspects described above, it was clear that the wing tip solution was better option. One crucial factor on this choice was the amount modifications the airframe required due to the project schedule. Additionally, the available payload in that configuration played a important role, since there were avionic system and fuel to be added to aircraft, regarding the combustion engine configuration. Also, it was assumed the MSU to weigh 2kg. A worst-case scenario assumption was also studied, in which the system mass was 3kg, assuming specific materials add to be used upon the harnessing and to manufacturer the container. A summary of the calculations is shown in the following graphics.

![Figure 11: Comparison of the mass distribution of each option for the gas engine configuration](image)

In case the MSU final mass was 3kg, the amount required to cancel its moment, on the increases almost 3kg. This represents a total of 11.7kg additional mass to aircraft for the installation of a system on board, which would represent 33% of the maximum take-off. For the wing tip, the total mass is 6kg, since the counterweight mass will be equal to MSU. The computations only confirmed the choice of using a wing tip configuration to install the MAD-XR was the best one.

At this point, other obstacles came up, regarding the technical operation of the MAD-XR. Due to the high intensity of the magnetic field on the N1 wing tip, the sensor analysis could be influenced, supplying unreliable data, compromising the success of futures operations. Therefore, it was established the magnetic noise generated by the aircraft and respective components on the sensor’s location should not be higher than 2nT, based on data from aircraft with similar operations [6].

Also, CAE alerted that due to performance and airworthiness issues, the cabling between MSU and MIU units required to be customized and to have a special type of connectors, which have a large thickness exceed, at some points, the wing geometry. This can be a problem for future purposes and maintenance issues, so it was recommended the whole system to fit in the wing.

These considerations were at basis for an optimization study of the wing, setting as objective a new concept that accounts for all these new requirements and the ones set previously.

4. Optimization

The intent is to modify the aircraft the minimum as possible. The wing, because it is the structure housing the sensor, is the only object of study in this project. It is assumed all other components, such as tail and fuselage, will remain as they were at the time of this work was performed.

Then, there were three main design variables, in which two were directly affected from the requirements: thickness $t$, because the large size on wiring connectors, and wing span $b$, to decrease the amount of magnetic noise generated by the VTOL engines;

The last variable is the wing area, $S$, and it was chosen due to its large influence on the aircraft generation of both lift and drag.

The goal of this optimization is to compute the wing parameters that will minimize the mass of fuel consumed, which is directly influenced by the amount of drag the aircraft needs to overcome.

**Thickness, $t$**

From the MAD-XR manufacturer, the sensor cabling has a large connector, which diameter is approximately 2.5cm. Therefore, it was established 3.5cm would be the minimum thickness of the wing, to allow all the cabling to pass through its cross-section. Also, from the aircraft designer experience, this thickness would also give the wing enough stiffness to endure the aerodynamic loads.

At this point, it was assumed, that the thickness-
to-chord ratio was going to be uniform along the wing. Knowing that its planform is defined to have a variable chord, it is necessary to guarantee a minimum \( t_{\text{tip}} = 0.035 \text{m} \) to match the design requirements. Therefore, it was chosen to set the thickness-to-chord ratio as a design variable.

**Wing Span, \( b \)**

Hansen’s magnetic characterization of the N1 [1] estimated the intensity of the magnetic field all over the aircraft. Having a minimum value of this parameter in the MSU’s location required an assessment of the distance this device should be from the VTOL engines. In other words, it required to know the variation of the magnetic field at the wing tip when the wing span varies. To avoid a having to evaluate the magnetic field intensity on every iteration, a surrogate model of the variation of the magnetic field along the wing span was developed, based on his model.

\[
B_{\text{wing tip}} = -1.87(b/2)^2 + 11.43(b/2) - 18.38 \quad (3)
\]

where \( b \) is the wing span.

With this, it was possible to find a minimum value that would the requirement of having a magnetic intensity lower than \( 2 \text{nT} \). Because it is a second-degree polynomial, has two solutions: 2.29 and 3.82. The second value was disregarded because the intent was to compute the minimum wing span.

For simplification, a minimum of 2.3m was chosen for the wing span upon the optimization, whilst the maximum was already define as 2.45m, due to cabling issues between MSU and MIU components of the MAD-XR.

**Wing Area, \( S \)**

The wing area was the only parameter that did not had a specific requirement from the entities involved in the project. However, when modifying an aircraft’s wing, the final result turns on an airplane with different characteristics and capabilities. Therefore, to define the range of values for this parameter, a methodology similar to aircraft design project was carried [7], with the selection of the wing loading \( (W/S) \) and the power-to-weight ratio \( (P/W) \). The wing loading or the weight-to-wing area ratio is defined as the ratio of the gross weight of the aircraft to the planform area of main wing. The power-to-weight ratio is defined as the ratio of power necessary for each phase of flight plan to the gross weight of the aircraft. The wing loading and the power-to-weight ratio are selected by considering the aircraft mission and its main requirements. The relevant parameters for the intended aircraft (propeller-driven) and its operation were: the cruise and stall speeds, range and endurance.

Then, using the design process from [7], the expressions were plotted in a chart, having \( W/S \) and \( P/W \) as axis. From this graph a design point can be chosen as long as it is contained in the admissible area that complies with all the criteria. The power loading \( P/S \) is 4.52 \( W/m^2 \) and the wing loading \( W/S \) is 318.5 \( N/m^2 \). The latter allowed to obtain the minimum value for the reference area, which, in this study, is assumed to be the wing area

\[
S_{\text{wing min}} = \frac{W}{W/S} = \frac{35 \times 9.81}{318.5} = 1.07 m^2 \quad (4)
\]

4.1. Aerodynamics

The aerodynamic characteristics on the optimizer were based on a model of the N1, based on experimental data and measurements and some theoretical assumptions from [7] and [8], with the addition of the wing tip pods of the MSU. A description of the input parameters for each component of the aircraft is shown in following paragraph.

**Wing**

At this stage, no airfoil had been chosen, which was not a problem because the model from [7] can be used by imputing parameters from airfoil characteristics and design, such as thickness-to-chord ratio and location of maximum thickness. Choosing an airfoil in such early stage would mean to prescribe the wing thickness-to-chord ratio, which could not result in the optimum solution. This approach allowed the optimizer to compute the best wing dimensions without major constraints.

Nowadays, there are several projects that couple airfoil with wing optimization, allowing to obtain a custom fully optimized wing, for a specific operation [9] [10]. However, it was not possible to develop those capabilities on the optimizer, wherefore some parameter were prescribed, based on nowadays practices, for model simplification: \( x/c_{\text{max}} = 30\% \), Oswald Coefficient = 0.8 and \( \lambda = 0.8 \).

**Wing tip Pod**

During the project timeline, it was required the N1 to fly with the MAD-XR mounted onboard. The solution was to design and rapid prototype a wing pod, that could house the MSU, as shown in Figure 13.
The final mass of the whole pod and MSU was 1.7kg, accounting for harnessing.

Assuming the pods could be treated as a blended body, the Sears-Haack approach for the fuselage was used to estimate the pods’ parasite drag. Due to its location at the wing tips, the interference factor $Q$ was defined as 1.25 [7].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [m]</td>
<td>0.42</td>
</tr>
<tr>
<td>Maximum Diameter [m]</td>
<td>0.16</td>
</tr>
<tr>
<td>Fineness Ratio</td>
<td>0.38</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 1: Wing Tip pod parameters

4.2. Optimization Process

With all variables and models defined, it possible to summarize the problem in terms of optimization notation: minimize $W_{fuel}$ by varying $s_{wing}$, $t_{wing}$, $b_{wing}$ subject to $t_{wing} \geq 0.035$

$s_{wing} \geq 1.08$

$2.3 \leq b_{wing}/t_{wing} \leq 2.45$

$(t/c)_{wing} = \text{constant}$

$L = L$

$V_{cr} = 50$

$V_{tr} = 40$

Initially, the objective was set to minimize the aircraft drag, $D$. However, due to the existence of various segment, which have different parameters and requirements, it was noted that the value for the minimum drag is not always coincident. In other words, the inputs that minimize the drag during the cruise stage may differ from the ones that minimize the patrol stage. Since the goal is to obtain a fixed-wing aircraft, the final solution must fit both stages.

Therefore, considering that, in steady, horizontal flight, $T = D$ and, knowing $T$ varies with the aircraft’s fuel consumption, by minimizing the total amount of fuel for the mission, the configuration that suits best for both segments is achieved. When optimizing an aircraft for cruise, designers typically look to minimize its drag [11], so the aerodynamic efficiency is as high as possible. When the goal is to optimize the loiter stage, the parameter of minimization is the flight power required [11], which is given by:

$$P_{req} = T \times V_{stage}$$

In this case, because $V_{stage}$ is defined as constant, the minimization can be done by just looking for minimum drag during loiter.

The diagram in Figure 14 helps to visualize how the optimizer works.

![Optimization Chart](image)

Figure 14: Optimization Chart

The design variables thickness, wing area and wing span are defined in a vector form $\vec{v}$, presented in the following form:

$$\vec{v} = (x_1, x_2, ..., x_m)$$

where $x_m$ corresponds to each scalar independent variable.

The aerodynamic model computes the aircraft’s drag, accounting with the wing tip pods, for each combination of inputs, for each flight segment: cruise and loiter. The computation returns an array of $j \times k$ matrices, which are the entries of a $1 \times i$ vector.

Simplifying em terms of mathematical notation, the process is defined as

$$[(D_{ij})_{cr} (D_{ij})_{ltr}] = f \left( (t/c)_{i}, S_{j}, b_{k} \right)$$

To guarantee that thickness at the wing root met the requirements, it was necessary to create a verification step, prior to the computation: if $t_{tip(i,j,k)} \geq 0.035(m)$, the script starts the optimization, if $t_{tip(i,j,k)} < 0.035(m)$, the final solution is not inside the feasible region, so the script disregards variables $((t/c)_{i}, S_{j}, b_{k})$ and advances to next set of input variables.

This avoids the computation of inconvenient configurations and the total drag $D_{ij}$ of each segment is compute for the variables that guarantee the requirements are fulfilled.

From horizontal flight equations, $T = D$, which means

$$P_{shaft(1)_{ij}} = \frac{D_{ij} \times V_{stage}}{\eta_{prop}}$$

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Additionally, it is necessary to account for 150W to supply electric energy to avionics.

Finally, the mass of fuel can be calculated putting all these parameters in the following equation

\[
m_{\text{fuel}_{ijk}} = C \times \left( \frac{P_{\text{shaft}_{ijk}}}{1000} \times \Delta t_{\text{stage}} \right)
\]  \hspace{1cm} (9)

where \(P_{\text{shaft}_{ijk}}\) is in Watts, \(W\), and the \(\Delta t_{\text{stage}}\) in hours, \(h\).

For the cruise segment, \(\Delta t_{\text{stage}}\) can be computed using motion equation and knowing the range and speed required for this stage. For the search segment, \(\Delta t_{\text{tr}} = E\).

In the end, the mass of fuel consumed is summed, considering losses and fuel reserve

\[
M_{ijk} = \left[ \left( m_{\text{fuel}_{ijk}} \right)_{\text{cr}} + \left( m_{\text{fuel}_{ijk}} \right)_{\text{ltr}} \right] \times 1.06 \hspace{1cm} (10)
\]

where \(M_{ijk}\) is the total fuel mass and \(\left( m_{\text{fuel}_{ijk}} \right)_{\text{cr}}\) is the sum of the fuel consumed on both cruise stages.

This computation allows to obtain the configuration the requires the least amount of fuel to carry the required operation, which can be considered as the most aerodynamically effective, once it minimizes the overall drag of the aircraft.

\[M_{\text{min}} = f (t_{\text{opt}}, S_{\text{opt}}, b_{\text{opt}}) \hspace{1cm} (11)\]

5. Result Discussion

5.1. Optimizer Output

Consider the following table:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Area (m^2)</td>
<td>1.08</td>
</tr>
<tr>
<td>Wing Span (m)</td>
<td>4.67</td>
</tr>
<tr>
<td>(\tau) (m)</td>
<td>0.231</td>
</tr>
<tr>
<td>Root Chord (m)</td>
<td>0.256</td>
</tr>
<tr>
<td>Thickness at Wing root (m)</td>
<td>0.044</td>
</tr>
<tr>
<td>Tip Chord (m)</td>
<td>0.205</td>
</tr>
<tr>
<td>Thickness at Wing tip (m)</td>
<td>0.035</td>
</tr>
<tr>
<td>Thickness-to-chord ratio</td>
<td>0.171</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>20.2</td>
</tr>
<tr>
<td>Total Fuel Mass (kg)</td>
<td>8.71</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Segment</th>
<th>W/O Pods</th>
<th>W/ Pods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dash to Target Area</td>
<td>0.0123</td>
<td>0.0178</td>
</tr>
<tr>
<td>Search/Patrol</td>
<td>0.0126</td>
<td>0.0179</td>
</tr>
<tr>
<td>Dash to Home Point</td>
<td>0.0122</td>
<td>0.0179</td>
</tr>
</tbody>
</table>

Table 3: Wing Dimensions

5.2. Post-Processing

Before start the discussion on the results, it is important to highlight this study did not account for the VTOL system, since complex aerodynamic phenomena would occur on that location on the wing. That evaluation requires the use of wind-tunnel testing or Computational Fluid Dynamics (CFD) to accurately characterize the generation of lift and drag of the fully equipped wing. Therefore, this study is conducted for an aircraft similar to the represented on Figure 15.

The addition of the pods at the wing tips have strong influence on the aircraft’s parasite drag, increasing its value in approximately 45% for all segments. The additional drag has a major consequence on fuel consumption, which, when comput-
ing the total mass for the reference N1 configuration, is about 4.7kg.

From Table 3, the fuel mass consumed for the optimal configuration is 5.77kg, which means an increase of 1kg on the fuel consumption, between the initial configuration and the optimized one, when the pods are accounted. This is mainly due to the difference between the thickness-to-chord ratios for both configurations, that caused an increase of approximately 19% on wing’s Form Factor, $F$, and, consequently, on the wing’s parasite drag. Also, the values for the lift and drag coefficients for the configuration without pods are similar to the ones computed in the initial aerodynamic model. This is mainly due to the similarity on the planform area difference between the thickness-to-chord ratios for both configurations, that caused an increase of approximately 19% on wing’s Form Factor, $F$, and, consequently, on the wing’s parasite drag. Also, the values for the lift and drag coefficients for the configuration without pods are similar to the ones computed in the initial aerodynamic model. This is mainly due to the similarity on the planform area between the optimized and reference wing.

In terms of manufacturing, this solution is very positive for the project and the aircraft because it is possible to assume the mass of the wing will not change, since, when using composite materials and keeping a similar thickness of skin, it is legt to assume $m_{wing} \propto S_{wing}$ [3]. However, a detailed study on the minimum thickness and total volume of composite materials required to manufacturer this structure should be performed, to accurately compute the optimized wing’s mass.

Analysing now the lift-to-drag on Table 6, the same situation verifies. In qualitative terms, this solution is possibly one of the best to fit problem, because the new configuration demonstrates similar aerodynamic characteristics to an airplane well-known from designing time.

<table>
<thead>
<tr>
<th>Segment</th>
<th>$C_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dash to Target Area</td>
<td>0.208</td>
</tr>
<tr>
<td>Search/Patrol</td>
<td>0.301</td>
</tr>
<tr>
<td>Dash to Home Point</td>
<td>0.175</td>
</tr>
</tbody>
</table>

Table 5: Lift coefficient $C_L$ from the optimizer

Figure 16: Drag sources during cruise: on the left configuration with unmounted pods; on the left the configuration with the pods mounted, generating 25% of the total aircraft drag assessed, given the fact it was proven fuel consumption varies with wing tip modifications [5].

**Magnetics**

When computing the magnetic interference at the optimum wing span, $b_{opt} = 4.67m$, the value from the approximation function defined on Equation (12) returns $β_{wingtip} = -1.88nT$. This value is not a surprise because any value of $b > 4.6m$ would give a value smaller than 2nT for the magnetic noise, due to the feasible region established in the beginning. However this only the approximation of a theoretical model. To prove the reliability of this result, a computational analysis was carried using a COMSOL magnetic model of the airplane, defined by Hansen [1] To analyse a particular coordinate, COMSOL allows to load the overall analysis and “probes” to scan a specified area. In this case, “probes” were used at both wing tips, $y = \pm 2.335$ which provided different results: the left wing tip measurement was $β = -2.27nT$ and the right wing tip was 2.04nT. This results are concordant with magnetic model from Hansen [1].

The error between the theoretical and the computational was computed using the following expression

$$ε = \frac{b_{comp} - B_{theo}}{B_{theo}} \approx 9\% \quad (12)$$

The value of the error between analysis was in the same magnitude as the errors registered by Hansen in its study [1], so the result was considered valid and successful, although the computational result is slightly higher than the requirements. In general, the final results represent a decrease of the magnetic noise at the wing tip of approximately 30% for the computational analysis and 35% in the theoretical.

In Figure 17, is possible to see the aircraft during a COMSOL analysis, since all constraints were satisfied, it is possible to conclude the optimization process was a success.

**6. Conclusions**

This work is included in a project that intends to develop a UAV, capable of conduct independent MAD missions, in search of submerged metallic vehicles, while performing VTOL from a ship. The final goal was to obtain an hybrid aircraft, that performs
VTOL with electric motors, and patrol and dash segments with a combustion engine, since it is required to execute search flight of 8 hours at 40m/s, after a 20nm dash at 50m/s.

When performing a magnetic survey, it is crucial to guarantee that the magnetometer is free from any magnetic noise source and that its data is accurately scaled and accounts for external interference. Therefore, it was chosen to locate the sensor at wing tip, taking into account the amount of mass required to keep the aircraft stable and the time to modify the airframe. This solution, however, needed additional modifications, due to magnetic clearance and component's accommodation.

An aerodynamic characterization of the N1 was carried, based on aircraft design theory and local collected data, from flight testing experience and measurements on the aircraft. A survey on N1 performance was carried for the required mission profile showed a fuel consumption of 4.7kg, considering the aerodynamic effects of the wing tip pods, where the MAD sensor is harnessed.

At this point, an optimization process was conducted, with the objective of minimize the fuel consumption. The design variables were the wing thickness-to-chord ratio, area and span, and the constraints were dictated from the magnetic, operational and aerodynamic disciplines involved in the process. To guarantee a feasible solution, a parametric optimization was used, where the total fuel consumption was computed for every combination of input variables. This resulted in a minimum value of 5.77kg for the mission listed above, accounting for the wing tip pods. Furthermore, the optimization method ensured that all constraints were satisfied during the process, obtaining a configuration that suits the project requirements.

This configuration dictated an increment of 20% in the aircraft wing span, slightly increasing the wing area, which gave the aircraft a similar aerodynamic efficiency when compared to the initial reference. The major accomplishment of the optimizer is a decrease of 30% in the magnetic noise, measured at new sensor’s location, which decreases the chances of obtaining unreliable analysis. However, dimensional requirements, such as the MAD sensor’s wiring accommodation, caused an increase in the wing thickness, which means an increment of 1kg in the fuel consumption.

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**References**


[2] Bruce Drinkwater. How to find a submarine (no, it’s not just a case of flicking the sonar on), 2014. [Accessed in 14-09-18].


