Docking Interface mechanism for Flow-me eVTOL aircraft

André Nogueira da Fonseca
andrenfonseca@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal
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Abstract

Urban air mobility is increasingly becoming a necessity, not only for the mobility of people, but also for the mobility of cargo, emergency medical products, among others. With the flow-me developed by CEiiA, the concept of air mobility is open to all possibilities. For this, the mechanism developed is crucial. It ensures the mechanical and electrical connection between the capsule and the aerial Vertical Take-Off and Landing (VTOL) system. Firstly, the development of the mechanism was based on CEiiA requirements and in accordance with aeronautical certification. For its development, a trial and error approach was followed by developing designs in CATIA v5 program until obtaining one that passes all the requirements, starting from an initial model already existing close to the requirements. A structural analysis was done to the mechanism using the hypermesh program. Secondly, the alignment system was developed in order to be able to align the mechanism to the maximum possible alignment error, with impact tests being carried out at the end to make it possible, using the abaqus program. Finally, the design of the integral system was made, integrating the closing mechanism with the alignment system. The choice of an appropriate loading system was also made, using models already available and adapting them to the final system.

Keywords: Urban air mobility, locking mechanism, Alignment system, Testing

1. Introduction

Today over 4 billion people live in cities, these cities are the epicenter of economic activity [14], with more than 80% of the global GDP being generated in cities and are also vibrant communities that need accessibility and good structure to connect than. As urban density increases, it brings poorer quality of life, poverty and poor air quality, this last one starting to be one of the main contributors for this degradation in lifestyle [11]. The European Union transportation alone accounts for 30% of total greenhouse emissions. Commuting to work in any mega-city has become a significant time sink for millions of people, for example in London the average commuter spends 227 hours a year in traffic. [12], and this trend is just getting bigger as the population grows. The need for a better and more sustainable transportation technologies to improve air quality and commute times is getting bigger and bigger. From electric cars to electric scooters, to high speed trains, this solutions will integrate our way life and are already doing so. Urban air mobility brings a new way to commute to work and transport goods using electric vertical take-off and landing (eVTOL) aircraft. Similar to an helicopter but without the pollution and at a reduced noise compared to. This three dimensional travel is a radical game-changer because it improve our radius of life in an environmentally responsible way. For example, a car can travel 20km in 40 min in the city, this option in 40 min can take the passenger for as far as 150km. With the increase of production and the transition for a mass market, the demand for eVTOL services will increase as the price becomes competitive. One of the companies interested in this new type of mobility is ceiia that came up with a new idea, the FLOW ME, that represents a three modular, aerial and terrestrial vehicle that will move people around the city by air and ground. Figure 1 illustrates the concept.

![FLOW ME](image1)

Figure 1: FLOW ME [6]
This vehicle will take a new approach for the mobility in cities. What distinguishes this flying car concept from the others are the 3 modular system, making the weight more distributed and allowing for better fuel efficiency when airborne. What makes this possible is the joint between the modules, this locking mechanism that will be developed will hold the modules together as well as actively free one and locking the other one. To accomplish this, a new concept that allows to share data and energy between modules is going to be presented. This concept could also be use in other 2 different applications such as space docking system, car docking and naval docking, with a few adjustments to it.

The mission profile is as described in figure 2.

![Figure 2: Mission profile](image)

The main objective is to search, choose, design and test a mechanical mechanism to hold the modules together and an alignment system to align the docking systems from the two modules to completely align the two modules to achieve a successful docking between the two.

2. Background

The design process of a docking system interface depends on its purpose and mission requirements. For the different purposes and mission requirements there are going to be different materials used, different control systems and different mechanical approaches for the docking system. Since the mobility system is going to carry persons inside, EASA regulation is required. The docking system designed has to have different characteristics in order to be safe to use. For example the docking system should be highly redundant, the materials to be used of great strength, stiffness and minimal weight. In this section, a scope of today’s technology is performed, from the state of urban air mobility to the materials used mainly in the aerospace industry crucial for the development of the mechanism.

2.1. Urban air mobility

As presented in the introduction and motivation section, urban air mobility comes in response to an increase of traffic in big urban areas. The eVTOLs are the main drivers behind this revolution in air travel. Electric vertical take-off and landing vehicles are light aircraft that can take off and land vertically, using electric motors to generate lift and batteries to store the energy needed. There are, over 100 eVTOL projects under development around the world[7]. However moving the project from development to test to commercial production is an heavy investment. The use for such vehicles include delivering packages and cargo, moving people across the urban environment from airport shuttles to sky taxis, as well as intercity for passenger services, and specific applications, such as military operations, 4 ambulances, search and rescue and fire fighting. The main keys in the development of such aircraft are firstly the design that includes what the aircraft looks like, the power drive and performance and making it as safe or safer than commercial aviation.

2.2. Docking

Docking mechanisms have always being very important in a system. These mechanisms connect parts, that when apart they can perform some tasks and when together they operate in other way, making the system less complex when separate. From docking system in trucks to space they operate in a range of ways. Actually, space docking is one of the most crucial parts of space flight. Gemini 8 [10], the international docking system standard(IDSS), ASSIST [5] and the Soyuz docking system and the pop.up next [15] are examples.

2.3. Connectors

Other important factor to have into consideration are the connectors between the two systems, this are achieved using connectors that transfer energy and data. The capsule and the air module have always to be connected by a data connection, this can be done physically or wireless. Also, when the air module lands in the charging pod it has to connect to charge, so a physical power with high current capacity is a must for the system.

2.4. Materials

The material that is going to be selected for the project has an important weight in the structural capability of the mechanism.

The materials analyzed are:

- **Aluminum alloys** - Aluminum alloys are the most common use in the airspace industry, they are lightweight, resistance to corrosion and when applied with other substances, they have different properties. The mostly use in the airspace industry are the 2000 series and the 7000.

- **Composite materials**

In the aerospace industry composites materials are one of the main drivers, they have high strength allied with low weight making the aircraft more efficient and with less power requirement. They are made from two or more
constituent materials with significantly different physical or chemical properties, that, when combined they produce a material with different characteristics from the individual components. Composite materials don’t present plastic deformation, they just present tensile strength.

- **Titanium alloys** Titanium alloys are metals that contain a mixture of titanium and other chemical elements. Usually Aluminum and vanadium. Such alloys have very high tensile strength and toughness (even at high temperatures). They are light in weight, have high corrosion resistance and the ability to withstand extreme temperatures.

The ASTM international [2] standard classifies the titanium into Grades, between grades it presents different treatment and/or composition.

2.5. Certification

Certification takes a big role in conceiving a new aircraft. In 2 of July of 2019 EASA has released a type certification for vertical take-off and landing (VTOL) aircraft, named Special Condition for small-category VTOL aircraft. Being the coupling mechanism a vital system of the aircraft the EASA SPECIAL CONDITION for VTOL a requires [4] it has to be designed and installed such that:

- each catastrophic failure condition is extremely improbable and does not result from a single failure;

- each hazardous failure condition is extremely remote;

- each major failure condition is remote.

So the system has to have redundant components, that if it fails there is a backup system that assures his integrity, in this case triple.

Also the safety factor is an important measure to design and evaluate. For the aeronautic industry usually a 1.5 safety factor is the minimum requirement [9].

3. Docking Mechanism Design

![Figure 3: Mechanism Development](image)

To design a docking mechanism an iterative based on trial and error process was defined and it is presented in figure 3. The iterative process defines a process to achieve a final product that is withing the requirements and tested to be ready for production [13]. Figure 3, illustrates in the flow chart the procedure taken. The steps taken in the design iteration process and presented in the flow chart are going to be analyzed step by step in the next subsections, achieving in the end the product intended.

The first step of the design iteration process is to define the requirements. The requirements comprehend the company needs for the product; they are the departing point of the process and the ones always to keep in mind while undergoing the next steps of the product development process. Next step, after analyzing the requirements is the concept generation, this comprehends the sketching of the different types of concepts analyzed in the state of the art that are presented today in the market. Then the concept is selected (concept selection). It follows the conceptual design where a concept is designed in the light of the requirements using as a base the concept selected above.

After the concept is designed, in D1 (design iteration point 1) it is decided if the concept designed is in the light of the design requirements good enough to continue the process. If yes it continues the pro-
cess, if otherwise a new concept has to be generated solving the problems found in D1. Next step of the process is the detail design. In D2 (design iteration point 2), the requirements not analyzed in D1 are analyzed and evaluated. Then, if all the requirements are met, the final product can go into pre-production.

3.1. Requirements

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight to carry</td>
<td>1000 kg</td>
</tr>
<tr>
<td>Factor of safety</td>
<td>1.6</td>
</tr>
<tr>
<td>Correspondence between the parts</td>
<td>completely fixed when locked</td>
</tr>
<tr>
<td>G force</td>
<td>4</td>
</tr>
<tr>
<td>Complexity</td>
<td>lowest possible</td>
</tr>
<tr>
<td>Weight of mechanism</td>
<td>lowest possible</td>
</tr>
<tr>
<td>Guidance/Alignment</td>
<td>has an alignment system</td>
</tr>
</tbody>
</table>

Figure 4: Requirements

In the planning section, other parameters to be considered in conjunction with the starting point are the requirements that the mechanism needs to have. Figure 4 represents a table that resumes what the CEiiA team wants in conjunction with the safety standards regulated by EASA certification [1]. Weight to carry is of 1000kg, the safety factor as well as the g force value are both certification needs issued by EASA. The correspondence between parts defines the need for a completely sealed structure between the top part and the bottom part when locked in place. Complexity is a qualitative measure, defining how complex the system is, a less complex one would mean cheaper production, so a better choice. The system being airborne, the weight is also a defining factor. In a docking system, an important part is the Guidance/Alignment, this make the docking possible even with some degree of deviation from the center. This system is going to be analyzed separately in other section due to its complexity. Despite of the above, in the concept selection and generation, as it is based in previous existent models, it is going to be analyzed all together for a better decision making.

3.2. Concept Generation

Concept generation is defined already in the background consists of 4 existing mechanisms, the Gemini 8, IDSS, ASSIST and the pop.up next mechanism.

3.3. Concept Selection

To analyze which mechanism was more close to the reality of ceiia vision a decision method was adopted. After analyzing different decision analysis methods, the M-MACBETH method [8] was opted. This method has the benefit of just requiring qualitative judgements about the difference of attractiveness between two elements at a time, in order to generate numerical scores for the options in each criterion and to weight the criteria, being easier to quantify the decision because of the lack of information from some mechanisms found and second for the CEiiA team to also evaluate together without the need of quantitative information to come with a solution for this part of the planning.

3.4. Conceptual Design - 1

The table above, represented in the figure 5 represents the results from the decision method adopted, MACBETH, to use quantitative values from the CEiiA team and using the method to represent it in a quantitative bases. It is concluded that the mechanism that better fits CEiiA needs is the pop.up next.

The first conceptual design is going to be based on the chosen model. The mechanisms consists, like the Pop.up next, in two rotating parts that upon contact it will rotate and lock. The software used for this task was CATIA.

Figure 5: Scores matrix

The first conceptual design is represented in the figure 6.

Figure 6: First Conceptual design

In the preliminary design review the mechanism does not pass one of the requirements. The requirement of completely fixed when locked is not achieved. The process can not be carried further, making it back to the conceptual design, where a
new concept design is going to be created having in mind the design flaw. Figure 7 represents it.

![First Conceptual design - flaw](image)

Figure 7: First Conceptual design - flaw

3.5. Conceptual Design - 2

In order to full fill the gap requirement, it was designed a new type of round mechanism with curvature and with an angled part, using, again CATIA software. This new type of mechanism was achieved by cutting as a sphere in the outer edges and with an angle in both of the components in the part that holds both structures together. The bottom part of the mechanism is shaped like, with a diameter of 100mm. Figure 8 represents the final concept achieved.

![Final conceptual design](image)

Figure 8: Final conceptual design

3.6. Detail Design

An analysis on the materials is carried out to the final conceptual design, which ones to use and to simulate with, for this it is evaluated the different options of materials available, described in the state of the art section. Aluminium 7075 being a relative strong alloy, with the highest tensile yield analyzed and being the most used alloy in the aerospace industry, widely available and easy to mold and produce pieces with it will be the one chosen to produce the mechanism. Using the density of the aluminium 7075 and the volume calculated using CATIA, the weight of the bottom part of the mechanism will be of 0.253 kg and of the upper part 0.229kg for a total weight of 0.482kg for the mechanism.

3.7. Critical Design review - structural analysis

In this critical design review, a test of the behaviour of the mechanism in terms of stress is going to be carried out, to analyze weather it can stand the requirements imposed by the CEiiA team.

The requirement of withstanding a weight of 1000kg means that the mechanism has to for \( g = 10m/s^2 \) (the true value is \( g = 9.81m/s^2 \), but in order to simplify it the value is rounded up for a more conservative value) the maximum force will be when locked and the gravitational force in the Z direction in relation to the base of the mechanism. Applying Newton 2nd law of motion: \( F=10000N \).

In order to be certificated the mechanism has to be allowed a g value of 4 and above this the safety factor of 1.5, comes: \( \text{Maximum force} = 10000 \times 4 \times 1.5 = 60000N \) The number of mechanisms planned to be used for each aircraft are 3 in an equilateral triangle, like illustrated in figure 9. The disposition in a equilateral triangle and the use of 3 mechanisms where the center of the equilateral triangle will be the gravity center of the VTOL aircraft means that for each mechanism the maximum force that needs to stand is \( \text{Maximum force}/3 = 20000N \).

To test if the mechanism can stand the maximum force allowed of 20000N the use of the Finite Element Method (FEM) is used.

![Mechanisms disposition](image)

Figure 9: Mechanisms disposition

3.7.1 Computational method to analysis stress

A FEM is going to be use to analyze the part in the stress point of view. After importing and solving problems on the geometry, and assigning a material, the structure is meshed. After a sensibly analysis of the mesh was performed to analyze the most efficient mesh size for the problem. The method used to perform the mesh convergency study was to analyze the stress and displacement in a point on the
geometry of the part, changing the mesh size, keeping the same other characteristics of the simulation, such as constraints, property and forces equal in every case simulated. The mesh sizes analyzed are going to be 10: 5mm, 2.5mm, 2mm, 1.5mm, 1.25 mm, 1mm, 0.875mm, 0.75mm, 0.625 and 0.5mm. The most significant force in the mechanism is going to be normal to the surface of the base, in the Z direction. The lappet of the mechanism are the ones in contact so are going to be the ones where the force is applied, for this at a first glance are going to be the ones under more stress or at least with more stress than the base of the mechanism, for this reason it was chosen a point in one of the lappets to analyze the stress with different meshes. The next two graphs in figures 10 and 11 represent the analysis performed.

In the graph displayed in figure 10, it can be seen that there is a point where the stress stabilizes, that point is for the mesh size of 1.25, after this point the curves jumps in smaller amounts up and down but is no longer with a down but a constant tendency. In the displacement for a mesh size of 1.25mm the curve is already almost stabilised too and it’s derivative close to 0, with a minor increment after as illustrated in figure 11. For this reasons the 1.25 mesh size it’s going to be the one chosen to perform and carry with the stress analysis of both the mechanisms, due to the second part being geometrically inverse of the first we can approximate that the mesh will behave in the same way.

After the boundary conditions were created. To simulate the bolts in the holes of the two parts, the same method as used in the sensibility analysis was performed. In order to simulate the contact between the two lappets a load was created in the contact areas of the two parts. The load type created was a pressure for better approximate the contact. Using the mass tool in hypermesh the total area of the lappet in contact in part 1 is of $1907.66 \text{mm}^2$ an for part 2 is of $1923.297 \text{mm}^2$. Knowing that the Force to be supported is 20000N for each mechanism, the pressure for the first and second parts are 10.5MPa and 10.4MPa, respectively.

The results obtained using the optistruct solver are represented in figures 12 and 13 with the left up corner of the figure representing the scale of stress observed in the elements.

For the aluminium chosen, the series 7075 artificially aged and heat treated T6, the stress for which it begins to yield it is of 503MPa. After this point the material starts to have plastic deformation, which is not admissible for the safe operation of the system.

The maximum stress in both parts is of 421MPa in the first part of the mechanism, being smaller
than the 503MPa, concluding that the mechanism is safe to operate within the requirements imposed.

4. Alignment system
The method implemented for product development of the guidance system is illustrated in the diagram represented in figure 14. It will begin in the space docking where the analysis of the space docking systems available and what they have in common was carried out. After taking the essential aspects of the space docking system into account a system was proposed and the posterior design was performed. After the design of the system the test of the system was performed to analyze until which point the system was safe to use, registering the limit and implementing in the future the control system. Also the maximum misalignment that the guidance system can take is going to be registered and posterior implemented in the control system as the maximum mechanical misalignment that the system can take to perform a safe landing and docking.

4.1. Space Docking
As seeing in the background, all the docking systems analyzed have one thing in common, a cone and a receptor shaped as the initial cone, based on this a system intended to allow a mechanical tolerance for the approach of the two systems is going to be created.

4.2. Proposed System
Taking the space docking in mind a system using CATIA V5 software was designed, consisting of two parts, one cone and one reception piece of the cone. The cone will be installed in the VTOL system and the reception in the capsule.

4.3. Design of the system
The design chosen is shown in Figure 15. It is composed of a 100mm radius cone and a reception part that fits in the cone with 300mm wide and 200mm in depth.

4.4. Test of the system
The method used for analyzing the two systems maximum acceleration is to analyze the maximum force that several impacts can have on both components. For this it was used the program ABAQUS to simulate the impact between the two structures, the cone and the reception. Due to the very low speed of collision, the impact can be approximated as a nonlinear contact between the two structures. After performing a sensibility analysis of the mesh, two cases are going to be tested in the aligned case and non-aligned.

4.4.1 Aligned case
For an ideal situation where the cone and the reception cone don’t have any protuberances and the metal is completely polish, the stress should be the same around all the surface in contact of the cone with the reception [3].

Theoretically for a completely polish cone, the contact between the two surfaces will be in all the lateral area of the cone. Given that \( A = \pi * r(\sqrt{h^2 + r^2}) \) defines the lateral area of the cone, the total area is of: 25289.33m\(^2\). The maximum pressure already discussed before is 298.7MPa, the maximum force allowed is of 6.986E6 N. Due to not have an infinite small mesh the stress will be irregular across the surface. Computationally, using the ABAQUS program and simulating the impact, the value computed of the maximum force allowed is of 8.383E6 N.
4.4.2 Non Aligned case

Firstly a theoretical analysis is going to be performed like the one carried in the case where the cone and the base where in a straight on position. The maximum pressure is of 294.7MPa and the area is the area that has a contact between the two surfaces. Analyzing the cube and using the abacus tools to measure the distance between two nodes. The contact area, or the area that has significant stress is of $1583,708566 \text{mm}^2$, with the pressure of 294.7MPa, the maximum force is of $4.74059\times10^5 \text{N}$. Computationally, using the ABAQUS program and simulating the impact, the value computed of the maximum force allowed is of $4.74059\times10^5 \text{N}$.

4.4.3 Conclusion of the method

In both cases, is acquired an average of the higher stress elements around the same area in each element, the cone and the base as is performed a theoretical analysis between the two systems. The theoretical analysis uses the simple $P = \frac{F}{A}$ and with the contact area, seen in the program, its computed the maximum force the contact between the two surfaces has to possess to the maximum pressure of the material, taking into account the 1.5 safety factor. The result for the aligned case is of $6.986\times10^6 \text{Newtons}$ and for the non-aligned case of $4.7409\times10^5 \text{Newtons}$. These results were analyzed in parallel with the program output. The program output for the aligned case a force of $8.383\times10^6 \text{Newtons}$ and for the non-aligned a force of $8.77\times10^6 \text{Newtons}$. This differences between the two cases is firstly because in the theoretical approach it is assumed a complete polish surface and the one output by the program the surface as irregularities due to being a finite mesh, this irregularities mean that the contact is not performed uniformly across the surface, resulting in stress differences. In reality there are always irregularities in the surface, being a completely polish surface impossible to achieve. The lowest value for the maximum force is the one going to be used for reference, being in this case the one found in the theoretical analysis in the non-aligned case of $4.7409\times10^5 \text{N}$. This contact force is very high, so, in terms of contact between the two surfaces, the system has a big safety margin.

5. Final Disposition

In this last chapter the final disposition on the surface of the capsule of the guidance system, the locking mechanism developed in the last two chapters and a possible charging system is going to be analyzed.

5.1. Requirements

CEiiA required an area of $1m^2$ on the bottom of the VTOL aircraft and top of the base of the capsule. For this reason the design of the all assembly had to be performed within this space.

5.2. Design of the full system

The final disposition of the locking mechanism has to be in the center of gravity of both the base of the capsule and the base of the VTOL. The arrangement of the 3 would be as illustrated in figure 16 as well as the guidance system. As illustrated in figure 16 the disposition of the locking mechanisms are in the mass center of the base. The 2 oblique lines from the vertices of the base coincide in the center. The 3 locking mechanisms are disposed in the vertices of an equilateral triangle that has as mass center the center of the base, making the conjunction of the 3 in the gravity center of the base. The 3 guidance mechanisms disposition in the base makes it just possible to the locking to be performed in one single side. The disposition of the alignment systems, allow for a gap between the two systems. The safety gap is half the radius of the cone of the alignment system, so 50mm. 50mm is the maximum displacement from the center point of the two systems, being tested in the last section, both impacts, one performed when both systems are completely aligned and other in the half extremity at 50mm from center. Finally figure 17 illustrates all the assembly between the bottom and the top of the mechanism.
5.3. Charging system selection

5.3.1 Requirements

- Fully Autonomous
- Capable of data transfer
- Completely waterproof
- High power ((above 200kw), but the higher the better))

5.3.2 Selection

In the state of the art section, some already existing connectors between two elements are analyzed. This connectors will allow for data and power connectivity between the air module and the capsule or charging pod. From the four connectors analyzed, the QCC, volterio, Easelink and Souriau, the best option for the system would be the Easelink. Souriau would not be a good option, due to its not autonomy capability of charging. The Volterio and Easelink are not completely waterproof just being certified for moisture. Flow me needs to mate also in rainy situations where the level of water is substantial higher for this reason and also for the mating system not having an alignment system to attach they are not going to be chosen for the system. QCC is the one that meets all the requirements. This charging solution can be adapted for the flow me system, where the pin would be attached to the air-drone system and the socket to the capsule or charging port.

6. Conclusions

Transportation is a global need and one of the pillars for a prosperous economy. In fact the better the transportation systems in a region the better infrastructure and as a result better opportunities come. This need allied with the need to become sustainable make the flow me a very important step in urban mobility. This new docking interface will allow for a more versatile and multi-functional approach for eVTOL, making them for multi-purpose. The capsule that holds passengers or cargo and the air system or drone that holds the systems for flight being separate allows for a more multi-use approach, for instance the air system can pick up different capsules, making the system more efficient. This solution will allow for the single purchase of the air system and different capsules that can be attached by the mechanism developed.

6.1. Achievements

It was designed and tested a valid structure capable of enduring the stress of the weight of the capsule as well as an alignment system strong enough to endure the stress of multiple collisions as well to create a margin for the two systems to dock with each-other. This allied with the disposition of both components in a way to keep a gap for after the control systems to have a safety margin to perform the approach.

6.2. Future Work

The system created and tested is the mechanical part of the system, the control systems and actuator need to be added to the system, the control systems as well the approach need to be performed in a way that ensures the docking withing the safety window of 50mm maximum from the center. Also the electrical connection between the two parts, to recharge and transfer data needs to be implemented in the system.

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