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EXECUTIVE SUMMARY OF THE THESIS

Mid-fidelity aerodynamic analysis and design of a fixed-wing eVTOL for the Martian atmosphere

LAUREA MAGISTRALE IN AERONAUTICAL ENGINEERING - INGEGNERIA AERONAUTICA

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1. Introduction

The Mars 2020: Perseverance Rover Mission conducted by NASA paved the way to the exploration of Mars with the employment of the first rotorcraft ever used out of the Terrestrial atmosphere, Ingenuity.

The helicopter successfully performed 72 flight in 3 years, for a total of about 128 minutes and 11 miles flown. Ingenuity consists of two contra-rotating rotors of approximately 1.2 m diameter, which provide vertical and horizontal thrust, a solar panel to recharge the battery pack, sensors and cameras stored inside a cubic fuselage, and four legs.

The state-of-the-art technology was used to minimize the overall mass (1.8 kg) and dimensions, leading to a production cost of about 81 million dollars, according to NASA [5].

1.1. Martian environment

The atmosphere of Mars, often referred to as the "Red Planet", is primarily composed of carbon dioxide, making up about 95.1% of its volume, with minor amounts of nitrogen (2.6%), argon (1.9%), and trace gases like oxygen and carbon monoxide.

NASA developed a simple numerical model of the atmosphere of Mars [6], reported in Equa-

tion 1, Equation 2 and Equation 3.

$$\text{For } h \leq 7,000 \text{ m: } \begin{cases} T = -31 - 0.000998h \\ P = 0.699 \exp(-0.00009h) \end{cases} \quad (1)$$

$$\text{For } h > 7,000 \text{ m: } \begin{cases} T = -23.4 - 0.00222h \\ P = 0.699 \exp(-0.00009h) \end{cases} \quad (2)$$

$$\rho = \frac{P}{R_{gas}(T + 273.15)} \quad (3)$$

where h is the altitude in [m], T is the temperature in [°C], P is the pressure in [kPa] and R_{gas} is the gas constant in [kJ/kgK]. Accounting for the molecular weight of the Martian atmosphere, that is approximately 43.3 g/mol, its numerical value is 0.1921.

The dynamic viscosity is only function of the temperature, according to the Sutherland's law expressed by Equation 4.

$$\mu = \mu_0 \left(\frac{T}{T_0} \right)^{\frac{3}{2}} \frac{(T_0 + S)}{(T + S)} \quad (4)$$

where μ is the dynamic viscosity in [Pas], T is the temperature in [K], μ_0 is a constant ($1.48 \cdot 10^{-5}$ Pas), T_0 is a constant (293.15 K) and S is a constant (240 K).

With the assumption of polytropic ideal gas, the speed of sound can be calculated with the expression reported in Equation 5, with all parameters expressed in SI units.

$$c = \sqrt{\gamma R_{gas} T} \quad (5)$$

On Mars, with a low temperature and low pressure environment, γ , namely the ratio between the isobaric and the isochoric specific heat is equal to $\frac{9}{7}$. The speed of sound calculated on the ground is therefore 244 m/s.

1.2. Motivation for fixed wing

It is clear that the exploration of Mars is not cheap at all. Furthermore, the rarefied atmosphere of Mars, together with its adverse weather conditions such as low temperatures and dust storms, makes flight on the Red Planet a difficult engineering challenge. However, there is a growing interest in the scientific community for the development of other flying machines to explore larger portions of Mars. The introduction of fixed wing, electric vertical take-off and landing (eVTOL), unmanned aerial vehicles (UAVs) is spot on for this purpose, exploiting the enormous advantages of an airplane wing to conduct an efficient flight for greater distances and still taking off and landing vertically in almost every location.

1.3. eVTOL model

This thesis represents the continuation of two previous works, which dealt with the conceptual and preliminary design of a fixed wing eVTOL UAV for the Martian atmosphere [1] and the aerodynamic study and optimization of low-Reynolds 2D airfoils [4].

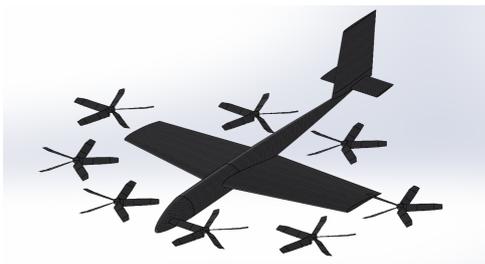


Figure 1: eVTOL model

The UAV was designed to fly in cruise at 90 m/s at 1,000 m altitude ($Re \approx 90,000$ and $Ma \approx 0.37$) for at least 200 km and to carry a 2 kg payload mass, namely a miniaturized gas chromatograph (CG) and a mass spectrometer (MS), used to conduct experiments with samples collected on the ground, and possibly sensors and cameras for high-quality video recordings of the planet.

The maximum take-off mass of the eVTOL was fixed to 20 kg, leading to a wing surface of 2.53 m² and a maximum shaft power of 3,500 W, estimated with blade element and momentum theory.

Afterwards, the number of rotors (eight) and their diameter (0.91 m) were decided and the battery pack and the solar panels were sized.

The low-Reynolds Ishii airfoil was optimized through genetic algorithm and adjoint method with CFD for several combinations of Reynolds and Mach numbers, in order to be used for both wing and rotor blades.

1.4. Goals

In this thesis a mid-fidelity approach is adopted to consolidate the outcomes of the previous works while introducing improvements and conducting further analyses to advance the project. Firstly, the design of the front rotors (tilting) and the rear rotors (fixed) has been carried out, including considerations on rotor solidity, blade average lift coefficient, blade twist, rotor collective pitch and blade airfoils.

Secondly, aerodynamic analyses of the full model have been conducted in hover, transition and cruise phases, with particular care on the loads generated by the rotors and the wing in cruise. Subsequently, the eVTOL stability derivatives have been estimated in cruise and the flying quality levels of all modes have been calculated. Later, an aeroelastic analysis of the clamped wing has been carried out to investigate the flutter phenomenon in the Martian environment.

To conclude, important remarks on the propulsive system and the structural properties have been made.

2. Numerical modeling

Several software have been used to accomplish the previously mentioned tasks, including a couple of open-source software developed by Politec-

nico di Milano’s Department of Aerospace Science and Technology, namely DUST and MBDyn, which represent the core of the thesis.

DUST is intended to provide reliable solutions to complex configurations with interactional aerodynamics, such as the Martian eVTOL. The core features of the software are the Vortex Particle Method (VPM) to simulate interactions and the mid-fidelity aerodynamic analysis available on commercial laptops.

In DUST there are several aerodynamic elements available: Surface Panel (SP), Vortex Lattice (VL), Lifting Line (LL), Non-Linear Vortex Lattice (NL-VL). By combining them it is possible to enhance the fidelity level of the aerodynamic simulations.

MBDyn is a multibody dynamics analysis software. It features the simulation of multidisciplinary systems, including rigid and flexible bodies subject to kinematic constraints. It can be coupled with external software, such as DUST, to perform aeroelastic simulations.

The body of the Martian eVTOL, including the fuselage and the lifting surfaces, has been modeled with an external Surface Panel mesh, as illustrated in Figure 2, in order to preserve its tridimensional shape and to accurately catch the interaction with the wake of the rotors.



Figure 2: eVTOL surface mesh

The mesh is structured on the lifting surface and on the fuselage nose while is unstructured on the rest of the fuselage. Regarding the number of panels, the Airbus Vahana model has been taken as reference [7]. Vahana is an eVTOL, single-seat, tilt-wing demonstrator produced by Airbus, whose model was used to validate the DUST codes. Overall, 10,838 surface panels were used for the body. Considering that the Martian eVTOL is half the size, an approximately equal number of panels has been em-

ployed to be conservative.

The rotor blades have been modeled with Lifting Line elements, augmented with c81 tables containing the airfoil characteristics. This approach allows to take viscosity into account and to correctly capture the loads on the rotors [8]. The rotor model is shown in Figure 3.

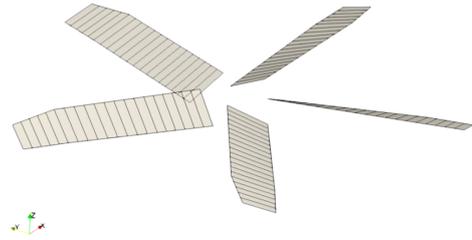


Figure 3: Rotor model

3. Isolated rotor design

For a start, the empirical relation between the rotor solidity and the blade average lift coefficient has been analyzed (Equation 6), considering the cutout effect and the tip loss.

$$\overline{C}_l = 6 \frac{C_T}{\sigma} (r_e^3 - r_i^3) \quad (6)$$

where σ is the rotor solidity, \overline{C}_l is the blade average lift coefficient, r_i and r_e are respectively the non-dimensional cutout radius and effective radius and C_T is the rotor non-dimensional thrust coefficient.

A high solidity rotor is needed to reduce the blade average lift coefficient, limited by the airfoil operative conditions in a low-Reynolds regime such as the Martian environment. Hence, it has been fixed to 0.30, similarly to the Advanced Mars Rotorcraft [3], and a total number of five blades per rotor has been considered a good trade-off, with the average chord being about 20% of the radius, with a moderate aspect ratio (5.33) and a not too low Reynolds number. Later, the theoretical optimal lift coefficient and twist distributions along the blade span have been calculated, with focus on the numerical values at the reference section, located at 75% of the blade span. In practice, a collective pitch of 28° (root section) has been selected to meet the hover requirement and a modest linear twist of -10° has been applied from root to tip.

Subsequently, the blade planform with a moderate taper ratio at the tip to prevent the drag rise

phenomenon has been created and the Reynolds and Mach numbers have been evaluated along the blade span, considering the Mach number limitation of 0.78 at the tip section, similarly to Ingenuity. At this stage, different airfoils have been selected among those optimized in a previous work [4] and the c81 tables have been created.

After defining the geometry of the rotor, the DUST model has been created and several simulations have been carried out in hover condition, the most demanding in terms of computational cost. A time and spatial convergence has been performed, choosing the number of revolutions, the number of time steps per revolution and the number of lifting line elements to obtain an independent solution.

To summarize, with 28° of collective pitch and 4,000 RPMs, the thrust, torque, and shaft power generated by the isolated rotor at time and spatial convergence are collected in Table 1, together with the figure of merit.

T	Q	P_s	FM
10.46 N	1.265 Nm	530.0 W	48.4%

Table 1: Rotor parameters at hovering at convergence

The eVTOL must be able to accelerate upwards during take-off at maximum RPMs. With a 20% excess of thrust, each rotor must generate 11.3 N of thrust. To meet this requirement the collective pitch of the rotor has been fixed to 30° for the following simulations. When hovering, the RPMs are slightly reduced.

After the complete characterization of the isolated rotor at hovering, other simulations have been carried out in transition and cruise phases, adopting linear relations between the airspeed and the nacelle inclination angle and between the nacelle inclination angle and the rotor collective pitch. The rotor collective pitch in cruise at 90 m/s has been set equal to 60° , considering the blade advance angle calculated with the velocity triangle.

All the four front rotors must tilt to meet the requirements of required thrust in cruise and in climb, while the four rear rotors stay in horizontal position and are shut down in airplane mode.

4. Full model aerodynamic analysis

Four simulations have been performed for the full model, composed by the body and the eight rotors, with the correct trim settings in terms of nacelle inclination angle, collective pitch and RPMs.

As shown in Figure 4 and Figure 5 the vertical thrust generated by the rotors properly match the required vertical thrust in all flight phases and the horizontal thrust is greater than the required horizontal thrust in transition, providing an adequate longitudinal acceleration, while it is equal to the eVTOL drag in cruise.

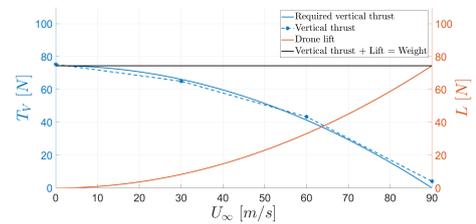


Figure 4: Vertical equilibrium of forces vs True airspeed

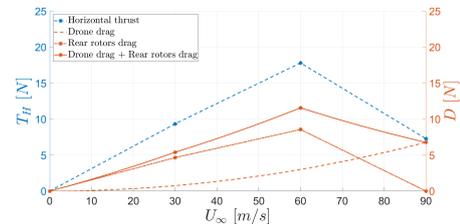


Figure 5: Horizontal equilibrium of forces vs True airspeed

The resistant torque and the shaft power have been extracted in all flight phases as well. The maximum installed shaft power must be at least equal to 5,000 W, greater than the 3,500 W hypothesized with blade element and momentum theory.

Both the electric motors and the battery pack have been revised, leading to an overall increment in mass equal to 4.6 kg and a mission range equal to 70 km.

The mass breakdown of the structural components performed in the previous work was much conservative. It is reasonable to assume a partial compensation of the increment in mass with state-of-the-art constructive method and

materials.

Furthermore, in the next 10/15 years, a significant improvement is expected for both the electric components and the miniaturized equipment. Therefore, the maximum take-off mass of the eVTOL has not been changed.

Subsequently, particular care has been posed to the loads generated by the rotors and the wing in cruise. The presence of the rotors cause increased dynamic pressure on the wing surface and create upwash and downwash effects. Overall, the wing lift is increased by 8%. The presence of the body cause a 2-5% increment in the loads generated by the front tilted rotors.

During the transition phase all rotors are active, as shown in Figure 6. Some interesting plots regarding the blade non-dimensional normal force as function of the radial and azimuthal locations have been created, remarking the difference between the advancing blade and retreating blade.

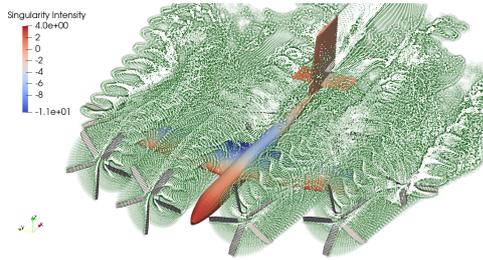


Figure 6: Full model in transition at 60 m/s - rotor wake and singularity intensity distribution

DUST well captures the vertical velocity flow field at hover, that is not perfectly symmetrical. Figure 7 shows a slice passing through the front inner rotors at convergence. The downward velocity reaches up to about 75 m/s in this flight condition.

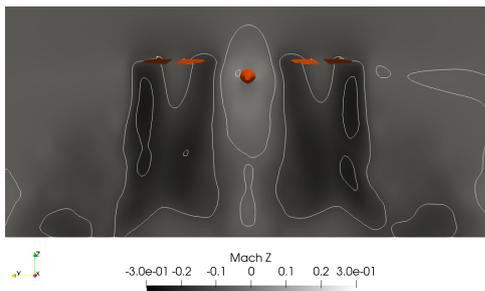


Figure 7: Z-direction Mach flow field - front view

5. Stability analysis

Under the hypothesis of linear aerodynamics and of decoupled longitudinal and lateral-directional dynamics, the static and dynamic stability derivatives have been estimated.

The static stability derivatives, those function of the angle of attack and the angle of sideslip, have been calculated by performing static simulations at several angles.

The dynamic stability derivatives, those function of the rate-of-change of angle of attack and sideslip and angular rates, have been calculated by imposing sinusoidal motions about the roll, pitch and yaw axes and by imposing a vertical and a lateral plunge oscillation. The single-point method [2] has been used to retrieve the numerical values.

Figure 8 and Figure 9 respectively show the maps of the longitudinal and the lateral-directional eigenvalues in cruise.

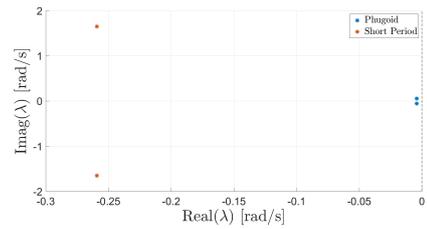


Figure 8: Map of longitudinal eigenvalues

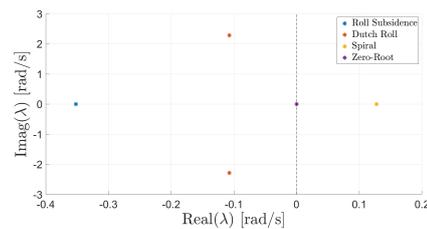


Figure 9: Map of lateral-directional eigenvalues

All eigenvalues have negative real part, except for the spiral mode. However a mild instability is typically accepted.

Finally, the flying quality level of each mode has been calculated and the possible implementation of a Stability Augmentation Systems (SAS) to improve the short period and the dutch roll damping ratios has been discussed.

6. Aeroelastic analysis

To conclude the technical development of the project a preliminary investigation of the flutter phenomenon of a clamped wing has been carried out.

State-of-the art materials such as a carbon-fiber tube spar, sandwich panel ribs and rohocell reinforcements have been employed to create the semi-monocoque model of the wing and the corresponding structural stiffness have been retrieved.

The software DUST and MBDyn have been coupled through the PreCICE interface and several simulations have been performed in the subsonic regime. As shown in Figure 10, no flutter instability is present.

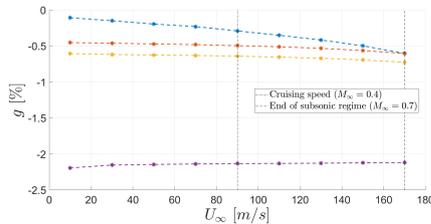


Figure 10: V-g diagram

7. Conclusions

This research highlighted the challenges and the opportunities associated with the design of a fixed wing eVTOL UAV for operations in the Martian atmosphere.

The mid-fidelity aerodynamic analyses allowed to study all the flight phases and provided more accurate results regarding the loads on the rotors. Despite the initial range estimation dropped to 70 km due to the increased shaft power it can still be considered an incredible outcome for the future missions of exploration of Mars.

The stability and the aeroelastic analyses confirmed that, from the flying quality and structural perspectives, a fixed wing drone is capable to fly on Mars and will be likely to be adopted for the future exploratory missions.

This project may still be improved with the creation of a detailed CAD model, an in-depth study of all junctions, and a FEM analysis. In addition, the control systems may be tuned and applied to the aircraft dynamics.

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