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Flight Mechanics & Scaling laws method in UAV design for Solar Planetary Missions

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Abstract:

In this survey, a mathematical model for a scaled model relative to a planetary UAV is presented considering 3 basic flight paths: climb, cruise and turn. The scaled model is in earth flight test aircraft (EFM) developed for the flight testing simulation of a Solar Planetary UAV. In the near future, the necessity of the exploration of solar planets and high performance communication links will be important. In this paper a planetary UAV's flight envelope is analyzed, a scaling mathematical method is proposed taking into account the atmospheric conditions, the velocity, and propulsion limits. This method leads to an updated carpet plot useful for the preliminary design calculations and in earth flight-testing. The development and the testing of a planetary UAV in earth conditions using the flight mechanics equations will be in high interest as different systems (propulsion, navigation etc) shall be tested functionally as early step during the test campaign.

Keywords — ***aerodynamics, scaling laws, high speed***

I. INTRODUCTION

The solar planets exploration is an interesting research activity during the latest years. The technological break-through innovation in engineering field such as telecommunications, material science, aerospace structures, satellites etc lead to opportunities for advanced missions in planets' exploration [1]. Creating colonies to solar planets with an atmosphere similar to Earth is under discussion for more than 30 years. The development of scientific techniques in UAV system integration is part of these efforts for upgraded aerospace structures. These UAV systems will carry scientific equipment, monitoring the planet surface, ice, oceans and transferring valuable data to the scientists. These need will lead to advanced UAS that could operate in planet atmosphere but previously could successfully pass the flight test operations in Earth. In this paper, a consolidated approach of the flight test scaling laws for Solar planet UAV are fully presented. The method takes into consideration the Flight mechanics in Planet's atmosphere, where the basic equations are scaled by various parameters and finally introduces the motion equations for «in Earth» Flight test program. Following this method, an unmanned air vehicle that is designed for operation in Mars, Europe, Titan or other solar planet, it will be successfully flight tested in Earth's Air Bases.

II. IN PLANET MISSION PROFILE

A. Description of flight envelope

The flight envelope of a planetary UAV is based on mission requirements that they are usually established by the Space Agency. For the current study, the following envelope is adopted:

1. The UAV is stored in a MotherShip-Spacecraft (similar to Space Shuttle) which is in orbital motion around the planet.
2. The UAV is detached by the spacecraft and performs a re-entry motion in planet's atmosphere. It uses limited ion-power thrusters for navigation and guidance, only. The motion is based on planet's gravity and lifting capacity of the UAV's wing body.
3. The UAV decelerates on operational altitude via angle of attack control.
4. The hybrid power system is activated and the UAV performs a) cruise, b) climb, c) turn, d) descent, e) loiter, phases inside the planet's atmosphere.

5. As the mission is accomplished, the UAV actuates the Rocket Engine, developing a speed near the planet's escape velocity. It goes to a steady ascent reaching the planet's sub orbital trajectories.
6. The UAV reaches the Mothership-spacecraft and fully attached on it. It is stored inside the hull.

This envelope's phases are fully presented in the Figure 1.

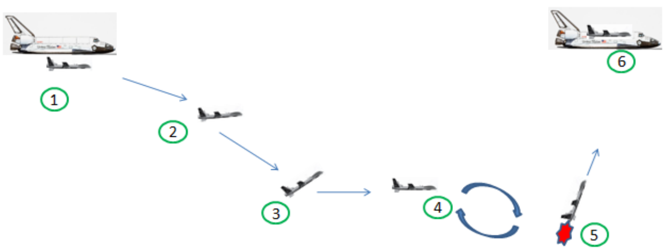


Fig. 1 Flight envelope

This study is concentrated on the phase 4, mainly. The method is applied on climb, cruise, turn sub phases where the UAV is moved inside the planet's atmosphere. The phases 1,2,3 and 5 are described as parts of the mission profile but they are transition phases and their kinematics/dynamics is better explained by Space Trajectories field.

B. *Space and Planetary Propulsion Systems*

For the in planet motion of the UAV, a hybrid type propulsion system is proposed using 2 different modes: a) an air/gas mixture-breathing using modified electric jet-engine/electric motorized turbine (powered by electric batteries/hydrogen fluid/solar arrays) and b) hydrogen gas-rocket engine for planet escaping phase. The propulsion system will operate in planet's atmosphere, mostly, using the air-breathing mode. The atmospheric air/gas mixture, it will be compressed by fan blades powered by propellant such as batteries/solar power or/and hydrogen liquid fuel (single or parallel functions).

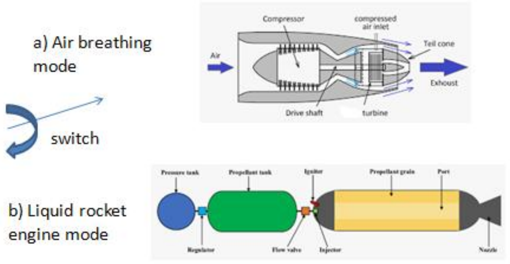


Fig. 2 Propulsion System Architecture

The compressed air-gas mixture will be further by-passed through nozzles, providing the required thrust.The compressor's blades are rotated through the electric motorized 'turbine'. The size of the intake, nozzles, and the mass-flow can be determined in accordance with the Space mission. Meanwhile, for the escaping flight mode the rocket engine will be used, switching to a rocket liquid propellant power system [2]. At this mode, the necessary thrust force will be developed overcoming the drag, gravitational acceleration and the atmospheric layers density/temperature composition. The thrust forces for the propulsion system are summarized in equations 1-2 for both modes (Figure 3).

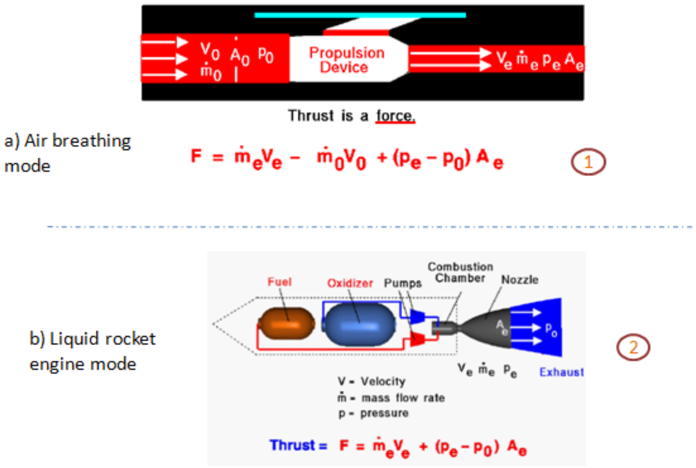


Fig. 3 Thrust force calculation for the 2 modes

In this paper, the principal values such the velocity and the necessary propulsion force will be addressed as functional parameters for the propulsion system. The propulsion system is a breaking through technology that it will be developed and tested separately.

C. Phase 1: In orbit

The UAV will be stored in a mother ship, such as a satellite or a spacecraft in orbit around the planet. It will be connected via umbilical cables to the Central Processing Unit of the mother ship retrieving monitoring data from the mission and power energy for its systems functions. A special attachment device will be placed in the specific location in the mothership supporting its operations. The orbital velocity is a fundamental value as the mothership can be moved in circular or elliptic trajectories around the planet [3].

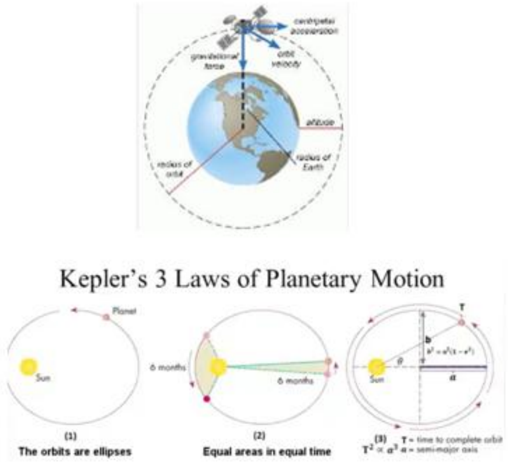


Fig. 4 Planetary orbits (circular/Kepler laws)

The Circular orbital dynamics and Kepler's laws could be used for the phase 1 as the mothership rotates around the planet and, assuming that the UAV moves with the mother ship at the same speed around the planet.

D. Phase 2&3: Dynamics of atmospheric re-entry

The planet atmospheric reentry is described by high velocity (Mach>15) and high Temperature effects [4]. The air/gas mixture density is a crucial parameter for the loads (both aerodynamic and thermal) prediction. This phase is completely another case study as the UAV is moving through the planetary atmosphere using the aerodynamic surfaces, its mass/inertia characteristics and propulsion system capacity, correcting the flight path trajectory.

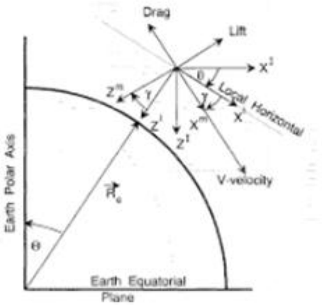
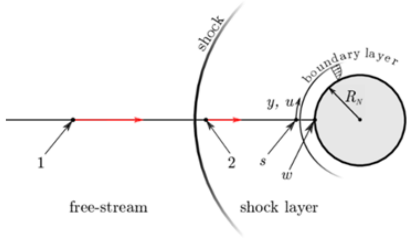


Fig. 5 re-entry` vehicle trajectory forces

This phase is governed by the lift to drag (L/D) ratio, the mass distribution, and the control system response. The Newton's equations for linear and rotational motion are applied setting basic flight conditions during the re-entry and UAV deceleration at operational altitude. Moreover, the heat load transfer through the thermal shield is another crucial parameter affecting the UAV weight. The heat loads per square meter are calculated as function of the air-gas mixture composition and the UAV velocity.



$$\dot{q}_w = \frac{0.763}{(\mathrm{Pr}_w)^{0.6}}(\rho_e\mu_e)^{0.4}(\rho_w\mu_w)^{0.1}\left[(h_o)_e - h_w\right]\left[1+(Le^{0.52}-1)\frac{h_d}{(h_o)_e}\right]\left[\left(\frac{du_e}{dx}\right)_t\right]^{0.5}$$

Velocity gradient from mod. Newtonian theory ~(1/R$_n$)

$$\frac{du_e}{dx} = \frac{1}{R}\sqrt{\frac{2(p_e - p_\infty)}{\rho_e}}$$

Fig. 6 Stagnation heat load and Fay Riddell heat transfer equation.

Phase 2 and 3 analysis is supplementary to the in-planet motion which is the operational mode. The phase 2 and 3 is referred to the UAV survivability under extreme loads that could affect the operational condition.

E. Phase 5&6: Rocket dynamics and escape velocity

The phases 5 and 6 follows the end of phase 4 where the UAV collects, stores but also transmits planetary data via the communication system to the mothership. The UAV goes to a high angle of attack motion or vertical ascent where the aerodynamic drag and weight are counterbalanced by the rocket engine's propulsion [2], [5].

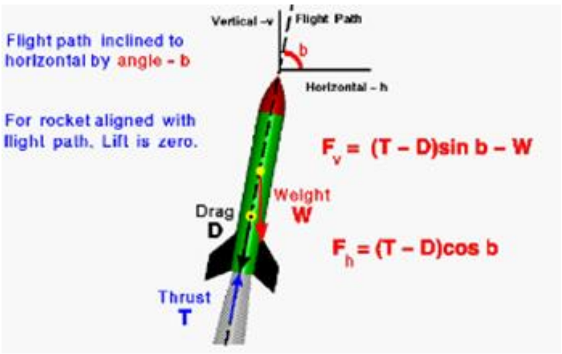


Fig. 7 vertical ascent-rocket engine propulsion

The escaping velocity shall be achieved by the UAV during this phase leading to a sub-orbit around the planet. Following this, the 'rendezvous' sub mission phase will be started for UAV and mother ship.

III. IN PLANET FLIGHT MECHANICS-PHASE 4

The phase 4 is the mandatory condition where the UAV will be scale for in earth flight-testing. The design parameters for the UAV (weight, fuselage and wing dimensions, empennage sizing, basic and auxiliary equipment and integrated systems) are set for investigation for specific Space mission. The UAV size and crucial parameters as wing loading (W/S) , thrust to weight ratio (T/W) , maximum g-load are carried out from the design procedure and fully applied to flight mechanics model [6]. The UAV flight model in planet motion is fully described by 3 flight mechanics equations, considering: 1) cruise, 2) climb, 3) turn. These equations are presented below:

$$\left(\frac{T}{W}\right)_p = q_p * C_{Dmin} * \frac{1}{(W/S)_p} + k * \frac{1}{q_p} * \left(\frac{W}{S}\right)_p, where,\ k = 1/(\pi * AR * e) \qquad (1)$$

$$\left(\frac{T}{W}\right)_p = \left(\frac{Vv}{V}\right)_p + \frac{q_p * C_{Dmin}}{\left(\frac{W}{S}\right)_p} + k * \frac{1}{q_p} * \left(\frac{W}{S}\right)_p \quad where,$$
$$Vv = V * \sin\theta\ \ (RoC) \qquad (2)$$

$$\left(\frac{T}{W}\right)_p = q_p * \left[\frac{C_{Dmin}}{(\frac{W}{S})_p} + k * \left(\frac{n}{q}\right)_p^2 * \left(\frac{W}{S}\right)_p\right] where,$$
$$\text{n is the load factor} \qquad (3)$$

The indication p is referred to UAV planetary flight. The scaling laws are introduced for various parameters such as a) physical & thermodynamic properties of air/gas mixture b) vehicle's velocity and c) the gravity acceleration between Earth and the Solar Planet. All the flight characteristics of the vehicle are correlated in order to be fully manageable for in Earth Flight Test.

A. *Scaling laws-Earth/Planet Correlation parameters*

Having the basic parameters from the UAV's design phase, the scaled factors are introduced for an equivalent Flight model (EFM) design and development for in-Earth Testing. The indication e is referred to the EFM developed for in Earth Testing. The basic assumptions' for the scaling laws are summarized below:

The aerodynamic coefficients are the same for in planet motion and in earth flight test operation. There is an aerodynamic similarity for the Reynolds and Mach numbers, both for the aircraft and the propulsion system. So, $Re,p=Re,_E$ *and* $Mo, p=Mo,_E$

The power limits are diferrent for the 2 flight conditions. The total power of the propulsion system must be adjustable managing the possibility for extra power.

Following these assumptions, the scaling parameters for the propulsion system and the aircraft are introduced describing the effect of the atmospheric/gravitational conditions.

B. *Scaling laws-Hybrid Propulsion System*

The scaling laws are not the same for the air breathing power system or the rocket engine. The compressed gas (hydrogen) in tanks where the gas pressure is very specific produces the rocket's thrust. The velocity at the nozzle's exit is function of the compressed gas pressure/mass rate and the thermodynamics in the rocket engine and fully unaffected by the planet's atmospheric conditions (closed system). The nozzle exit pressure is usually the same with the static atmospheric pressure as the nozzle can adjust the cross section area. Thus, the thrust is the same for both planetary and earth terrestrial flights (Pe=Po).

$$T_{p,rocket} = T_{e,rocket} \leftrightarrow \lambda_{rocket\ propulsion} = \lambda_{rp} = 1 \quad (4)$$

For the air breathing propulsion system, the thrust production is function of the atmospheric conditions and the nozzle's exit velocity. The thrust is given by the equation:

$$T = m' * (V_e - V_0) \overset{\cdot}{+} (P_e - P_0) * A_e = \rho_0 * V_0 * A_0 * (V_e - V_0) + (P_e - P_0) * A_e = \gamma * R * T_0 * M_0 * \Delta Mach + (P_e - P_0) * A_e \qquad (5)$$

It is assumed that the pressure exit is close the atmospheric condition (Pe=P0). This condition could be achieved by variable nozzle cross-sectional area. Setting, p and e indicators, we set the thrust ratio equals to:

$$\frac{T_p}{T_E} = \frac{\gamma_p * R_p * T_{0,p}}{\gamma_E * R_E * T_{0,E}} * \frac{\rho_p}{\rho_E} = {n_{vel}}^2 * n_{dens} = \lambda_T \quad (6)$$

This scaling procedure could be used further for the development of the hybrid propulsion system.

C. *Scaling laws-Flight Mechanics*

In general, the scaling factors are applied in major parameters such as a) wing loading, b) dynamic pressure, c) true air speed, and d) load factor. These scaling factors are presented below:

Wing loading and gravitational acceleration scaling:

$$\frac{W/S_P}{W/S_E} = \frac{m*g_P}{m*g_E} = \frac{g_P}{g_E} = \lambda_g \quad (7)$$

The dynamic pressure in compressible flow:

$$\frac{q_p}{q_E} = \frac{0.5*\gamma_p*P_{0,p}*M_{0,p}^2}{0.5*\gamma_E*P_{0,E}*M_{0,E}^2} = \lambda_q \quad (8)$$

The Mach number is used for scaling in compressible flows, so:

$$M_0 = \frac{V}{\sqrt{\gamma*R*T}} \rightarrow \frac{V_p}{\sqrt{\gamma_p*R_P*T_P}} = \frac{V_E}{\sqrt{\gamma_E*R_E*T_E}} \leftrightarrow \frac{V_P}{V_E} = \frac{\sqrt{\gamma_p*R_P*T_P}}{\sqrt{\gamma_E*R_E*T_E}} = \lambda_v \quad (9)$$

The load factor refers to the ratio : n=L/W for the turning, maneuvering conditions. It could be written as:

$$n = q * C_L * \left(\frac{1}{W/S}\right) \ (10)$$

Thus, the load factor ratio is : $\lambda_n = \frac{n_{LF,p}}{n_{LF,e}} = \frac{q_p}{q_e} * \frac{W/S_E}{W/S_p} = \frac{\lambda_q}{\lambda_g}$ (11)

D. *In Earth Flight Mechanics*

The in-planet flight mechanics equations are re-written to in earth flight mechanics equations through the scaling factors for the gravity, velocity, dynamic pressure and load factors. These equations are used for the scaled model development & testing in earth atmospheric conditions.

Cruise:

$$\left(\frac{T}{W}\right)_E = \left[\frac{\lambda_q}{\lambda_T}\right] * C_{Dmin} * \left[\lambda_g^{-1}\right] * \frac{1}{(W/S)_E} + k * \left[\frac{\lambda_g}{\lambda_q*\lambda_T}\right] \frac{1}{q_E} * \left(\frac{W}{S}\right)_E, \ (12)$$

Climb:

$$\left(\frac{T}{W}\right)_E = [\lambda_T^{-1}] * \left(\frac{Vv}{V}\right)_p + \left[\frac{\lambda_q}{\lambda_g * \lambda_T}\right] * \frac{q_E * C_{Dmin}}{\left(\frac{W}{S}\right)_E} + k * \left[\frac{\lambda_g}{\lambda_q * \lambda_T}\right] * \frac{1}{q_E} * \left(\frac{W}{S}\right)_E \qquad (13)$$

Turn:

$$\left(\frac{T}{W}\right)_E = \left[\frac{\lambda_q}{\lambda_T}\right] q_E * \left[\frac{C_{Dmin}}{(\frac{W}{S})_E} * \left\{\lambda_g^{-1}\right\} + k * \left\{\frac{\lambda_g*\lambda_n^2}{\lambda_q^2}\right\} * \left(\frac{\mathrm{n}}{q}\right)_E^2 * \left(\frac{W}{S}\right)_E\right] \qquad , (14)$$

The modified equations are the basis for the preliminary design of the aircraft using the carpet plot method. The selection of the main aerodynamic coefficients shall be based on analytical methods, experimental data or numerical calculations. The comparison plots between the Planetary UAV and EFM scaled model calculations could be figured out together for further design aspects.

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