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Demonstration of Aerodynamic Control Manoeuvres in Very Low Earth Orbit using SOAR (Satellite for Orbital Aerodynamics Research)

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Abstract

Aerodynamic forces have often been proposed as a possible means to perform a variety of different attitude and orbit control manoeuvres in very low Earth orbits including pointing control, constellation and formation management, and re-entry interface targeting. However, despite interest and numerous studies conducted in this area there is has been lack of on-orbit demonstration of these manoeuvres beyond simple proof of aerostability and some operational use of differential drag for constellation maintenance. SOAR (Satellite for Orbital Aerodynamics Research) is a CubeSat mission and part of DISCOVERER, a Horizon 2020 funded project to develop technologies to enable sustained operation of Earth observation satellites in very Low Earth Orbits. SOAR is due to be launched in 2020 with the primary aim to investigate the interaction between different materials and the atmospheric flow regime in very low Earth orbits. This satellite, with its set of rotating aerodynamic fins, also offers the unique opportunity to demonstrate and test novel aerodynamic control methods in the very-low Earth orbit (VLEO) environment. This paper presents the approach to demonstrate novel aerodynamic control methods in-orbit that will be used on the experimental SOAR Cubesat. The aerodynamic manoeuvres and associated control methods selected for demonstration are first described. Simulations of the aerodynamic control manoeuvres and expected satellite dynamic behaviour are also presented, demonstrating potential advantages for spacecraft operations which can be achieved by utilising the natural aerodynamic forces present at these lower orbital altitudes.

Keywords: (maximum 6 keywords)

Nomenclature

Acronyms/Abbreviations

ABEP	Atmosphere-breathing electric propulsion
ADCS	Attitude determination and control system
CMG	Control Momentum Gyroscope
EO	Earth observation
FMF	Free molecular flow
GSI	Gas-surface interaction
GTO	Geostationary/geosynchronous transfer orbit
LQR	Linear-quadratic regulator
LVLH	Local-vertical local-horizontal
OBC	On-board Computer
PID	Proportional-integral-derivative
SOAR	Satellite for orbital aerodynamics research
VLEO	Very-low earth orbit

1. Introduction

Very-low Earth orbit (VLEO), altitudes below approximately 450 km, offer a number of benefits to the operation of spacecraft. In particular, Earth observation platforms can profit from increased spatial resolution with reducing altitude or alternatively can carry smaller and less massive optical payloads [1]. In order to realise these operational benefits, the DISCOVERER project [2] is focused on foundational research and technology development to enable sustained operations at lower orbital altitude.

The principal challenges of spacecraft operations in VLEO are increased exposure to highly reactive atomic oxygen that can erode spacecraft surfaces, and the increased atmospheric density at lower altitudes that contributes to larger aerodynamic forces, principally drag which reduces the orbital lifetime. Efforts to address the reduced orbital lifetime in these orbits include mitigation of drag through electric propulsion, including concepts for atmosphere-breathing electric propulsion (ABEP), and reduction of drag through the identification of novel aerodynamic materials.

However, the increased atmospheric density and associated aerodynamic forces of larger magnitude in VLEO can also be exploited, providing the opportunity to perform aerodynamic attitude and orbit control. To date, a variety of aerodynamic attitude and orbit control techniques and manoeuvres have been proposed, studied, and simulated. In some limited cases these manoeuvres have been demonstrated in-orbit and used operationally.

In orbit control, attention has principally been focused on orbit maintenance and formation flying manoeuvres. The foundational work in this area was presented by Leonard [3], in which notional drag plates were used to control the relative distance between two spacecraft, a method termed differential drag. Further studies have extended this concept, for example utilising the body of the spacecraft to provide a varying drag force [4], considering adaptive and optimal control strategies [5,6], and incorporating significant sources of uncertainty such as atmospheric density and drag coefficient [7]. Differential drag has since been demonstrated in-orbit by the ORBCOMM constellation [8], AeroCube-4 mission [9], and the Planet Labs Dove satellites [10,11]. Differential drag methods have also been proposed for atmospheric re-entry interface targeting [12–14] and to generate out-of-plane separations for constellation deployment [15].

In the previously discussed methods, aerodynamic drag has been utilised to enable control as the magnitude of lift forces available in the free-molecular flow regime of Earth orbit is small. However, if efforts to identify novel materials that have improved aerodynamic characteristics are successful, then the use of lift forces may be enabled. Examples of the use of lift forces for aerodynamic orbit control include enhanced formation flight and rendezvous manoeuvres [16–18] and inclination correction for descending Sun synchronous orbits [19].

Aerodynamic torques can also be used to control the attitude. Aerostability (aerodynamic stabilisation) has been used by spacecraft in-orbit to provide natural flow pointing behaviour, for example by the DS-MO [20], PAMS [21], and GOCE [22] spacecraft. Aerodynamic attitude control has also been proposed for pointing control [23–25], to assist detumbling operations [26], momentum management in GTO perigee raising operations [27], and was employed by MagSat to provide trim and momentum control [28,29].

Novel aerodynamic control methods are currently being developed within the scope of the DISCOVERER project with a focus on those with application to Earth observation missions. Within this research, pointing, trim, and momentum management manoeuvres using combinations of aerodynamic torques and conventional attitude actuators have been studied for different aerodynamic platform concepts [30].

The scientific CubeSat SOAR (Satellite for Orbital Aerodynamics Research) [31] associated with this project offers a unique opportunity to test and demonstrate novel aerodynamic control methods in the very-low Earth orbit environment.

The aerodynamic control manoeuvres and associated methods that are planned for in-orbit demonstration on this spacecraft will be described in this paper. Simulations of the expected performance in the VLEO environment are also presented.

2. Satellite for Orbital Aerodynamics Research

SOAR is a 3U CubeSat that has been principally designed to investigate gas-surface interactions (GSI) in the VLEO environment. The aim of the mission is to provide important in-orbit validation data for ground-based experiments that will be performed in the ROAR (Rarefied Orbital Aerodynamics Research) facility at The University of Manchester. SOAR is due to be launched into VLEO from the ISS in 2020.

SOAR, an evolution of the ΔDsat design [32], features a unique combination of two payloads to achieve the scientific mission objectives. A set of four rotating fins, located towards the rear of the 3U geometry as shown in Figure 1, are used to expose different materials to the oncoming flow at varying angles of incidence. This enables the investigation of GSI and aerodynamic coefficients for the different material coatings. An ion and neutral mass spectrometer (INMS) is located on the forward-facing surface of the CubeSat, providing in-situ measurement of the oncoming flow conditions including density, composition, and velocity. A 3-axis gyroscope unit (IMU), fine sun-sensors, and 3-axis magnetometer provide sub-degree attitude determination whilst an on-board GPS receiver also provides precise position and velocity information. A tetrahedral reaction wheel assembly provides capable attitude control in three axes and is supported by magnetorquers for initial detumbling operations and momentum management.

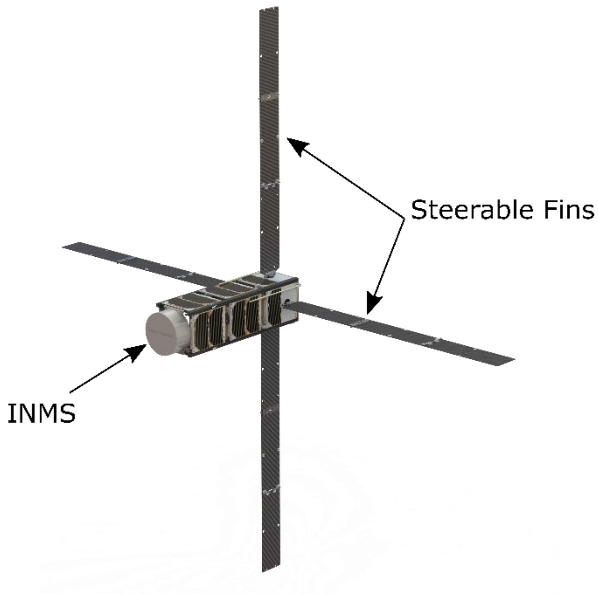

Figure 1 3U geometry of SOAR (Satellite for Orbital Aerodynamics Research).

The four independently steerable fins on SOAR provide the opportunity to perform aerodynamic control manoeuvres during the mission lifetime. However, for the primary scientific investigation the surfaces of these aerodynamic panels will be finished with different material coatings. The panels are therefore likely to have varying aerodynamic performance properties that may increase the complexity of implemented control schemes on the spacecraft.

Table 1 Mission and physical properties of SOAR

Spacecraft Properties	
Body length (including INMS)	0.365 m
Body height/width	0.1 m
Aerodynamic panel length	0.58 m
Aerodynamic panel width	65 x 10^{-3} m
Aerodynamic panel thickness	1 x 10^{-3} m
Total Mass	3.5kg
Centre of mass (from –X)	0.15 m
Principal moments of inertia	I_{xx} : 0.057 I_{yy} : 0.074 kg m^2 I_{zz} : 0.074
Reaction Wheels (Astrofein RW1 Type A)	
Spin axis moment of inertia	654.5 x 10^{-9} kg m^2
Maximum angular momentum	1.2 x 10^{-3} Nms
Maximum torque	7.2 x 10^{-8} Nm
Orbit Properties	
Initial altitude (ISS)	~400 km
Inclination	51.6°

3. Aerodynamics in VLEO

For orbiting bodies, aerodynamic forces and torques are generated by interaction with the residual atmosphere. With reducing altitude, these forces and torques increase and in VLEO can contribute significantly to the orbit and attitude dynamics of spacecraft.

3.1. The VLEO Environment

The density of the atmosphere increases approximately exponentially with decreasing orbital altitude. In VLEO (typically defined as orbits below 450km), the atmospheric density can therefore be orders of magnitude greater than at traditional LEO altitudes (see Figure 2). The influence of solar output on the atmospheric density is also considerable. In addition to the approximately 11-year solar cycle, seasonal, and diurnal variation is also present.

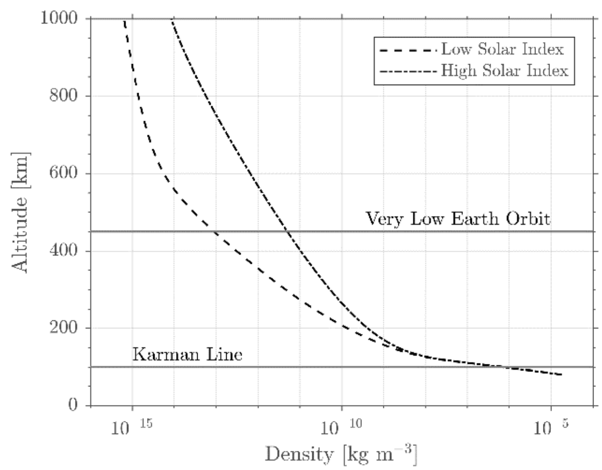

Figure 2 Atmospheric density with altitude using NRLMSISE-00 [33] model and ECSS reference solar and geomagnetic index definitions.

Whilst often deemed negligible at higher altitudes, the flow environment in VLEO is of importance as aerodynamic forces and torques are generally the dominant source of perturbation [34]. Based on the Kundsen number (Kn, ratio between the mean free path of a particle and the characteristic length of a body in the flow), the regime in VLEO is generally classified as free-molecular flow (FMF). Under the conditions of FMF ($Kn \geq 10$), particle-particle interactions are rare in comparison to the interactions between an incident particle and the surface in the flow, and the former can therefore be neglected.

3.2. Aerodynamic Force and Torque

For a given surface exposed to an oncoming flow, the force experienced can be equated to the density ρ, velocity V, a reference area S_{ref}, and the associated force coefficient C_F:

$$F = \frac{1}{2}\rho V^2 S_{ref} C_F \quad (1)$$

Equivalently, the torque generated by such a surface can be expressed by considering a moment coefficient C_M and a reference length of the spacecraft L_{ref}:

$$T = \frac{1}{2}\rho V^2 S_{ref} L_{ref} C_M \quad (2)$$

The force and moment coefficients are dependent on the nature of the interaction of the surfaces with the oncoming flow, and under the assumption of FMF conditions, are therefore dependent on the GSI characteristics.

3.3. Gas-Surface Interactions

The force experienced by a surface during a collision with an oncoming particle can be determined by considering the exchange of momentum or energy during the interaction. GSI characteristics are known to vary with a number of parameters including the material properties, incidence angle, surface roughness and contamination, atmospheric composition, and both surface and incident particle temperature.

A variety of models have been developed to capture the effects of these different parameters, with varying level of complexity and success. In the simplest of these models, typically used to in space engineering applications, an expression for the exchange of energy/thermal or momentum, an accommodation coefficient (α or σ respectively), is used to broadly describe the nature of the GSI present.

Two primary modes of GSI can be considered initially, specular reflection and diffuse reemission. In specular reflection, an incident particle is assumed to be perfectly reflected with no thermal accommodation ($\alpha = 0$). Contrastingly in diffuse reflection, an incident particle is assumed to be thermally accommodated to the surface ($\alpha = 1$) and is consequently thermally reemitted from the surface with a given distribution, typically centred about the surface normal. For different GSI models variation of the accommodation coefficient between these conditions can generate a range of different reflection or reemission distributions which describe the average effect which occurs at a surface. Common models used in orbital aerodynamics applications include Sentman [35], Schaaf and Chambre [36], Schamberg [37], and Cook [38].

The significant presence of atomic oxygen in VLEO leads to high adsorption of this species and its reaction products to typical spacecraft materials. These surfaces have been shown to be close to or fully accommodated and therefore demonstrate predominantly diffuse reemission behaviour [39]. Consequently, the available lift produced by surfaces coated with these materials is small in comparison to the magnitude of the drag force [40].

3.4. Aerodynamic Coefficients

Analytical expressions for the force and moment coefficients can be generated from these GSI models for simple geometries (eg. flat-plate, sphere).

For more complex spacecraft shapes, the geometry can be modelled as a mesh of flat plates for which the individual force and moment coefficients can be calculated and summed together to provide the total body contribution. These so-called panel methods (eg. ADBSat [41]) are appropriate under the conditions of FMF and for geometries where multiple surface reflection are not expected to take place (ie. convex geometries). Shadowing of surfaces from the flow by other parts of the geometry also requires careful consideration.

Alternative, but typically more computationally expensive methods of calculating aerodynamic coefficients include direct simulation Monte Carlo (DSMC) [42], test-particle Monte Carlo (TPMC), and ray-tracing techniques [43].

4. Aerodynamic Attitude Control in Orbit

4.1. Aerostability

Aerostability (aerodynamic stability) is the ability of a spacecraft to align itself with the direction of the oncoming flow. This can be achieved passively through geometric design of the spacecraft such that restoring torques are generated when the nominal attitude of the spacecraft is disturbed.

The conditions for aerostability can be defined [44] as in Equation (3), providing necessary relationships between the static stability derivatives of the spacecraft with the inertia matrix. Using these conditions, statically stable spacecraft can be designed considering the environmental conditions, external spacecraft geometry, and relative position of the centre of mass.

$$\begin{aligned} -\frac{q}{3\omega_0^2}\frac{S_{ref}L_{ref}}{I_y}C_{m_\alpha} > 1 \\ I_y > I_z \quad (3) \\ \frac{q}{\omega_0^2}\frac{S_{ref}L_{ref}}{I_z}C_{n_\beta} > 1 \end{aligned}$$

However, whilst static stability can be generated in FMF, aerodynamic damping is negligible. Without any additional input, a spacecraft will naturally oscillate about the oncoming flow direction in response to an initial disturbance. Additional attitude actuators are therefore necessary in order to reduce these oscillations and provide

Aerostability has been demonstrated in orbit by a number of different spacecraft with varying design. The DS-MO satellites featured an aerodynamic skirt extending behind the main body a gyrodamper [20]. In comparison, the cylindrical spacecraft PAMS relied only on the relative position of its centre of mass to provide the necessary restoring torques whilst magnetic hysteresis rods were used to provide the damping effect [21]. The slender GOCE spacecraft featured rear-mounted aerodynamic fins and was equipped with magnetorquers [22].

4.2. Pointing

Aerodynamic torques can also be used to point a spacecraft towards a direction or target of interest. Control in only the roll-axis was proposed by Auret and Steyn [24] using a pair of forward mounted control paddles. Three-axis control has also been proposed using a split-panel shuttlecock geometry [23] and a feathered panel configuration [25].

However, for currently characterised materials with close to full accommodation, the available remission distribution only allows small pointing angles to be achieved without contribution from additional attitude actuators.

4.3. Trim

Aerodynamic control surfaces can be used to reject external perturbations and assist the maintenance of a stable attitude. In VLEO, this may include compensation of the relatively predictable atmospheric co-rotation in inclined orbits or torques associated with solar radiation pressure or gravity gradient for example. Trim in this manner can reduce the requirement for alternative attitude actuation with possible benefits in power consumption and indirect management of momentum build-up.

The principal of aerodynamic trim can also be used to avoid the build-up of internal momentum when the spacecraft presents an asymmetric geometry into the flow, for example during off-axis pointing manoeuvres. The MagSat mission [28,29] demonstrated aerodynamic trim in-orbit using an extendible boom in the pitch axis which was used in coordination with the gravity gradient to bias the pitch of the angle spacecraft.

4.4. Momentum Management

Aerodynamic control can also be used to actively reduce the internal momentum that can build up in conventional attitude actuators such as reaction wheels and control momentum gyroscopes (CMGs). If performed actively throughout the mission this type of control may be able to assist an attitude control system from becoming saturated or entering a singular state. Alternatively, external torques produced by aerodynamic control can be used reactively to perform momentum-dumping, desaturation, or to remove a singular condition.

MagSat [28,29] also used a combination of the adjustable aerodynamic and gravity gradient torques to perform momentum management in the pitch axis.

4.5. Impact on Orbital Lifetime

The effect of aerodynamic control on orbital lifetime requires careful consideration in order to avoid rapid or premature deorbit of the spacecraft. Whilst the previously discussed manoeuvres may have operational benefits, these must be traded off against the potential impact to the mission through reduction of the mission lifetime.

In each of the proposed manoeuvres, the presence of additional control surfaces exposed to the flow will increase the drag experienced by the spacecraft and therefore increases orbital decay. Efficient use of the control surfaces is therefore required to preserve the mission life.

The identification of specularly reflecting materials would enable the prospect of lift-based aerodynamic control forces and torques that would allow the control surfaces to be exposed to the flow less, reducing the drag experienced. Alternatively, drag mitigation, for example using electric propulsion or ABEP, can extend the mission lifetime and increase the scope for aerodynamic control manoeuvres.

5. Aerodynamic Attitude Control of SOAR

The development and demonstration of novel aerodynamic control methods for VLEO spacecraft is an objective of the Horizon 2020 DISCOVERER project [2]. Aerodynamic control manoeuvres for a nominal set of conceptual aerodynamic spacecraft geometries (shuttlecock, feathered, and neutrally-stable disc satellite) have been studied, and their results presented in a companion paper [30]. This paper presents the implementation of these developed methods to for in-orbit demonstration on SOAR.

5.1. Control Strategy

In order to implement the aerodynamic control manoeuvres on SOAR a quaternion-feedback PID controller with an intelligent integrator [45,46] was adopted [30]. The selection of the proportional, integral, and derivative gains in this scheme are determined using a linear-quadratic regulator (LQR) with a penalty formulation to encompass saturation of the actuators.

For the momentum-management task, an infinite-horizon LQR feedback loop is implemented for the aerodynamic control input whilst the reaction wheels independently perform the attitude control task. In order to avoid conflict between the attitude control and momentum management tasks the time response of the two control tasks are separated.

5.2. Concept of Operations

In order to perform the demonstration of aerodynamic control manoeuvres on SOAR the orbital altitude must be low enough that the aerodynamic torques have the necessary control authority. A characterisation of the different perturbing torques experienced by the SOAR at different altitudes is presented in Figure 3. The residual magnetic dipole torques

Given the geometry of the spacecraft and the expected atmospheric density at launch, the altitude of the spacecraft needs to be lowered to around 300km before demonstration of the aerodynamic manoeuvres can commence.

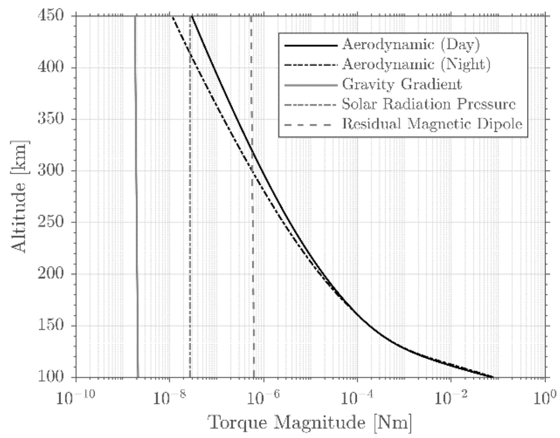

Figure 3 Relative magnitude of perturbing torques for SOAR pitched at 3° (from LVLH) and steerable fins counter-rotated to 30°.

Implementation of the aerodynamic control on SOAR involves coupled use of the ADCS to measure the current attitude of the spacecraft, the OBC to calculate the desired aerodynamic torque, and the aerodynamics payload to apply the selected configuration of the steerable fins. Simultaneous use of the reaction wheels may also be necessary for some of the control manoeuvres.

Implementation of the control manoeuvres on the OBC requires the respective control methods and steerable fin configuration algorithms to be compatible with the on-board processing capability and data storage. Extensive databases of aerodynamic coefficient sets based on multiple variables (angle of attack and sideslip, altitude, rotation angle) are therefore not recommended and linearised approximations are required.

5.3. Aerostability

The aerostability of SOAR can be examined by considering the response in pitch and yaw against angle of attack and angle of sideslip. The gradients shown in Figure 4 and Figure 5 demonstrate aerostable behaviour in both the minimum and maximum drag configurations.

The corresponding dynamic response of SOAR without any control actuator input is shown in Figure 6 for an altitude of 250km. It can be seen that the maximum drag configuration provides significantly better attitude control. However, in both configurations the attitude errors and rates become large over time and would be unsatisfactory for most useful applications.

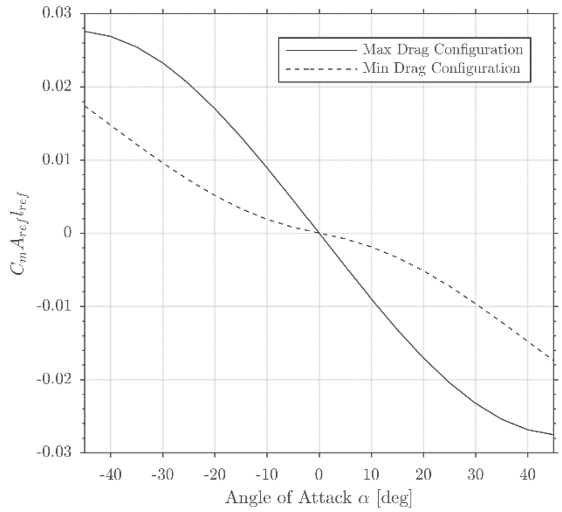

Figure 4 Pitch stability of SOAR in the minimum and maximum drag configurations.

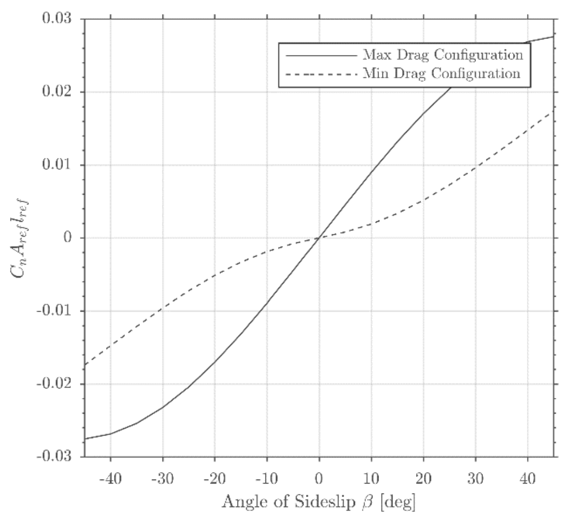

Figure 5 Yaw stability of SOAR in the minimum and maximum drag configurations.

In order to provide dynamic stability and reduce oscillatory motion, additional damping is required. On SOAR, these torques can be provided by the on-board reaction wheels or alternatively the magnetorquers. The motion of SOAR with simple proportional (in roll) and damping (in pitch and yaw) control is shown in, demonstrating significantly improved attitude control performance with slower rates and smaller pointing errors.

In-orbit demonstration using SOAR will seek to confirm this behaviour and investigate the reaction wheel torques required to provide a stable attitude with variation in the orbital altitude.

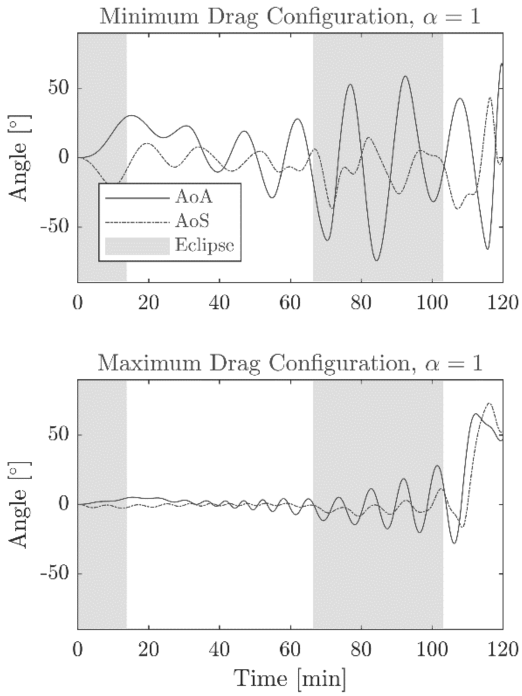

Figure 6 Uncontrolled attitude of SOAR in minimum and maximum drag configuration at 250 km.

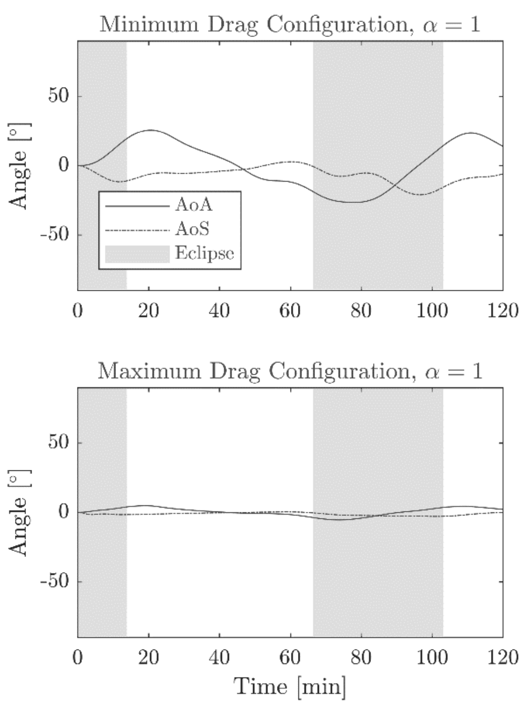

Figure 7 Attitude of SOAR in minimum and maximum drag configuration at 250 km with simple proportional control in roll and damping control in pitch and yaw.

5.4. Pointing

Aerodynamic pointing control and trim manoeuvres will also be attempted with SOAR in-orbit. The four independently steerable fins can be used to generate aerodynamic torques in all three body axes.

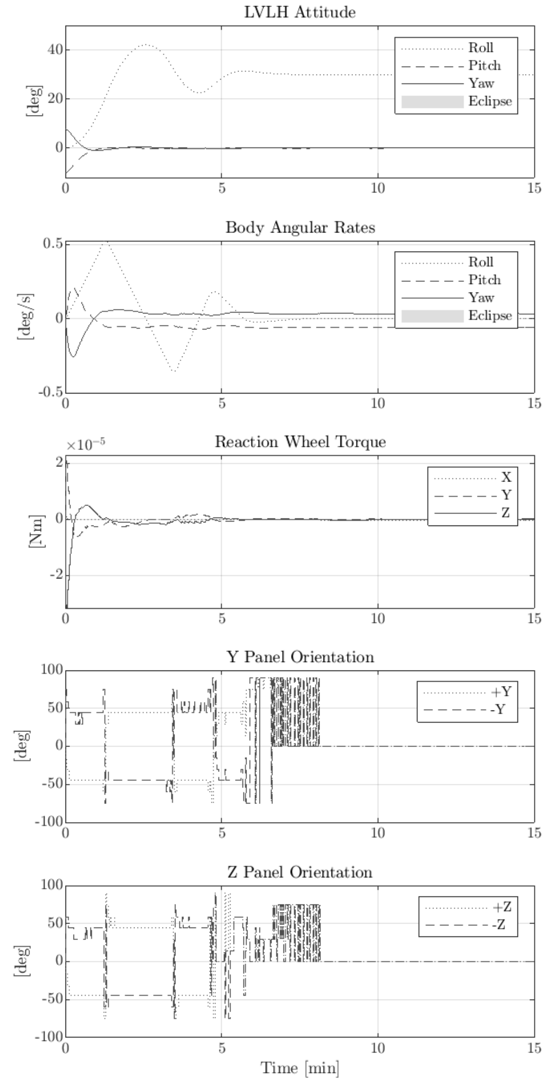

Figure 8 Aerodynamic roll control manoeuvre to 30° at 250 km with reaction wheel control in pitch and yaw.

The simplest demonstration manoeuvres involves aerodynamic roll control whilst the motion in the pitch and yaw axes is controlled using the reaction wheels. SOAR should ideally utilise only symmetric counter-rotation of opposing steerable fins to generate roll torques when the spacecraft is aligned closely to the flow-pointing direction. However, in an inclined orbit atmospheric co-rotation and thermospheric winds generate disturbing torques. Compensating torques in pitch and yaw will therefore be demanded by the aerodynamic control loop.

A representative simulation for a control manoeuvre in roll from 0° to a target of 30° is shown in Figure 8. The roll manoeuvre is performed successfully through selection of counter-rotated panel configurations. However, as the spacecraft is stabilised about the target attitude some significant actuation of the aerodynamic panels is instructed rather than their return to the nominal configuration. To reduce this behaviour, saturation avoidance logic can be introduced into the aerodynamic control method, avoiding the selection of high-drag aerodynamic configurations when lower drag selections may provide similar torque profiles. This will also limit the effect of the aerodynamic attitude control on orbit decay, increasing lifetime.

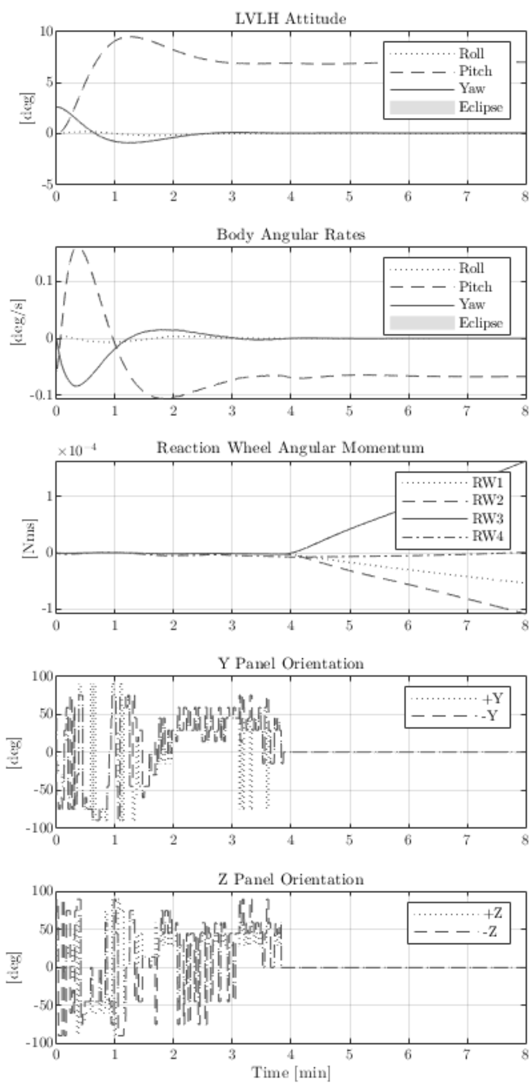

Figure 9 Aerodynamic pitch control manoeuvre to 8°, yaw aligned with the LVLH reference frame, and reaction wheel control in roll.

Aerodynamic control in the pitch and/or yaw axes is somewhat more challenging. In the presence of external perturbations, asymmetric and complex configurations of the steerable panels may be required. In order to simplify the manoeuvre, the reaction wheels can be commanded to control the spacecraft in the roll axis only.

An example of an aerodynamic pointing manoeuvre is shown in Figure 9Figure 8 where a target of 8° in pitch is demanded, whilst the attitude in yaw is to be aligned with the LVLH reference frame. In this scenario the requested attitude is successfully attained using the aerodynamic panels. However, after the manoeuvre is complete the reaction wheels can be seen to trend directly towards saturation as they try to maintain the offset attitude from the flow. In this case, further usage of the aerodynamic panels could enable the spacecraft to maintain this attitude for a longer period, but at the expense of increased orbital drag.

5.5. Momentum Management

SOAR will also demonstrate management of internal angular momentum during the mission. In these experiments, the aim of the control loop is to minimise the rates of the reaction wheels (and the corresponding angular momentum) by producing opposing aerodynamic torques. An implementation of this type of control can be performed with the spacecraft attempting to maintain an attitude offset from the flow-pointing direction.

In a 51.6° inclined orbit, secular perturbing torques will cause an accumulation of angular momentum in the reaction wheels. Without any intervention from the aerodynamic panels, the reaction wheels are shown in Figure 10 to fully saturate after a period of around 7 minutes. After this time, the reaction wheels are unable to provide further control actuation to oppose the current disturbing torques and the pointing performance of the spacecraft is compromised. In these conditions, magnetorquers would generally be used periodically to desaturate the reaction wheels.

The aerodynamic control surfaces can be used to mitigate this accumulation of angular momentum, allowing the reaction wheel control operations to continue for a much longer period of time without interruption. This is demonstrated in Figure 11 in which the angular momentum of the reaction wheels is sustained away from the saturation limits over a period of 100 minutes. Furthermore, during this period the spacecraft is shown to be stable about the demanded pointing angles in pitch and yaw despite the presence of disturbing torques and the inputs from the aerodynamic panels.

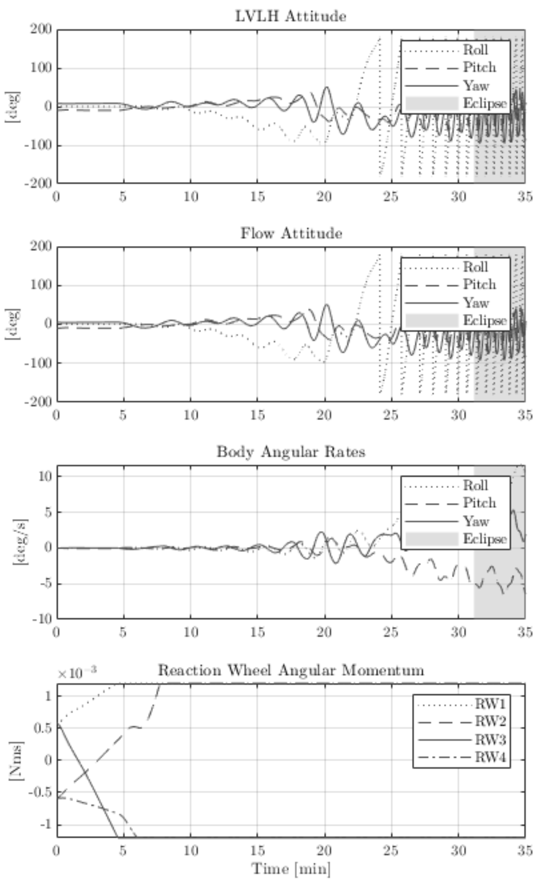

Figure 10 Saturation of reaction wheels whilst an attitude of -10° in pitch and 8° in yaw (with respect to LVLH) is demanded without any aerodynamic control input.

6. Conclusions

The on-orbit demonstration of aerodynamic control on the scientific CubeSat SOAR was discussed and proposed control manoeuvres presented. The expected attitude control performance that can be achieved using the combination of traditional attitude control actuators and unique aerodynamic steerable fins was shown through simulated results.

The spacecraft is expected to demonstrate aerostable behaviour and pointing capability in the VLEO environment, but requires additional attitude actuator input in order to damp oscillations and provide fine pointing capability. The aerodynamic control surfaces are also expected to be able to assist in the momentum management of the platform at these lower altitudes, enabling operation of the reaction wheels for longer periods before desaturation is required. However, whilst the simulated results are indicative of the basic behaviour achievable using the SOAR platform, additional complications of the real mission need to be considered.

The primary mission objective of SOAR is to investigate gas-surface interaction of different materials in VLEO and their corresponding lift and drag coefficients. The aerodynamic control surfaces will therefore be coated with different materials with varying aerodynamic behaviour. A more complex model for the expected forces and torques that can be generated by the independent rotation of the steerable fins is therefore required.

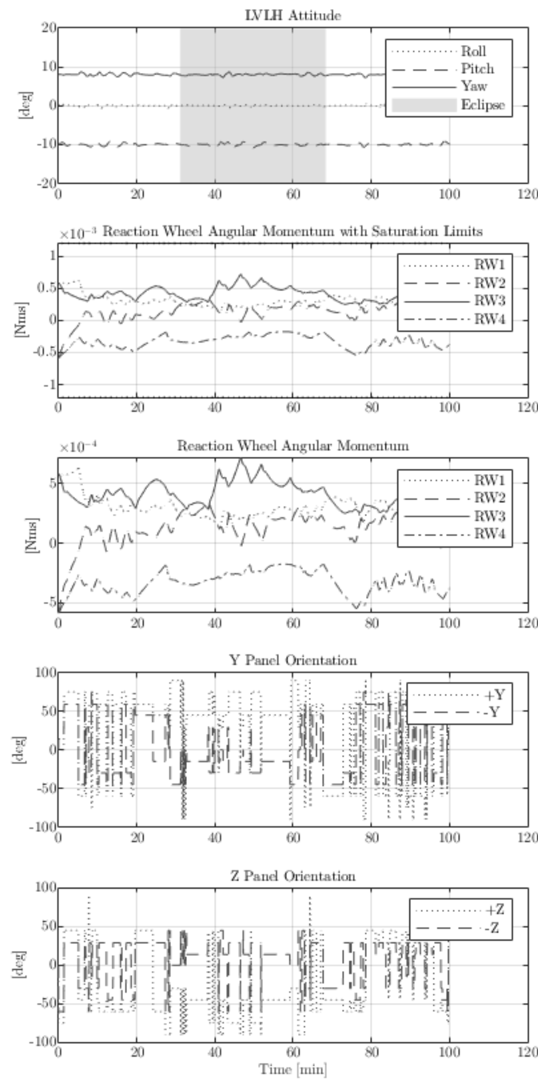

Figure 11 Momentum management whilst an attitude of -10° in pitch and 8° in yaw (with respect to LVLH) is demanded.

Development and improvements to the aerodynamic control methods need to include consideration for the specific hardware limitations, including the system sampling rate, attitude determination sensor accuracy and noise, and the reaction wheel performance. The controller must also be made compatible with the on-board computer and available resources.

Acknowledgements

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