Development of a Thrust Vector Control Mechanism for Deorbitation System

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Abstract

The following paper details development of design features employed within the Thrust Vector Control (TVC) which is a part of deorbitation propulsion system based on a Solid Rocket Motor (SRM). The main purpose of TVC mechanism is to increase the controllability of the deorbitation system. The TVC design incorporates outside flaps working as deflectors, moved in and out of the exhaust stream of a nozzle at the exit plane. Deflection of the flaps produces a lateral force relative to the direction of axial thrust, resulting in a moment with regards to the vehicle's center of gravity, which results in a turn. The paper presents the design process, accompanying analysis and ablation test results with lessons learned and conclusions.

Introduction

The TVC described herein was designed as a part of the development of a deorbitation system based on an SRM. The paper focuses on the mechanism adding necessary details concerning SRM performance.

After over 60 years of the space age, there is an urgency to think about protection of the space environment: to prevent continuous growth of debris and to prevent orbits from becoming entirely inhospitable. This is especially true with a space private sector growing rapidly and offering new technologies and approaches which result in a revolution with regards to the costs of spacecraft launch and payload capabilities. Those implications are going to be reflected in the design philosophy – less conservative design, accepting larger risk, and introducing technologies with no space heritage. Commercializing space by competing entrepreneurs brings a lot of new possibilities, but it also results in a rapid increase in the number of space vehicles (including large constellations) which generates space traffic, especially at low-Earth orbit and geostationary orbit regions. Non-operating satellites need to be removed from orbits to make space for newcomers. Hence, a reliable end-of-life strategy has to be implemented as soon as possible. One of the most effective methods to mitigate the risk of new space debris generation is its end-of-life utilization. A deorbiting SRM with a TVC system is one potential solution. The main advantages of using a dedicated deorbiting system based on an SRM are: relatively high density performance, low system complexity, storability and autonomy [1] [2]. By adding TVC to an SRM, a deorbiting system gains better control over an end-of-life maneuver: its attitude and orientation, ensuring that the final trajectory would be performed accurately and safely. The TVC system should compensate trajectory misalignments and uncertainties resulting from spacecraft's center of mass, inertia, flexibility of appendages, sloshing, thrust variation from motors and different burning time in order to correctly set the spacecraft's position during the deorbitation maneuver. The proposed design can be optimized precisely, depending on satellite needs and deorbiting requirements. The mechanism presented herein is focused on increasing capabilities in terms of thrust deflection angle, which is an angle defining how thrust is inclined with regards to the axis of the SRM. According to the analysis, it is possible to obtain ~10° for thrust deflection.

Concept

The selected concept using outside flaps has been chosen based on a thorough trade-off, preceded by a detailed state-of-the-art research including thrust vectoring methods from missiles, launchers and aircrafts.

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The trade-off included four different, preliminarily selected TVC concepts: gimbal, outside flaps, supersonic split line [3] and movable nozzle. It took into consideration 17 driving attributes/selection criteria chosen based on the application purpose, and main coinstraints coming from the SRM design (i.e., long-storage capabilities, operation duration, envelope size, test capabilities, or thrust losses). The outside flap solution scored the highest in the trade-off for the particular application. At the later stage of the concept investigation, attention was paid to the kinematics of the solution and envelope size. The chosen concept is a variation of a Fowler mechanism, commonly used in aviation wing design. It benefits from the kinematics: flap slides backwards before hanging inwards. This setup allows less volume for the mechanism, as the geometry of the design can be circumscribed to the maximum diameter of the SRM. Moreover, in a stowed position it does not elongate the axial dimension (that could be problematic in terms of configuration onto a satellite having in mind the SRM parameters). Also, in terms of steering and control the design should benefit as the variable-ratio design could be adjusted according to specific needs. The system is rather lightweight (unlike a gimbal where the entire motor needs to be moved). Moreover, the method requires only minor changes in the SRM design – adding aditional mounting features on the nozzle part (unlike the movable nozzle where the motor design is highly affected by incorporating a TVC). The main disadvantage is axial force (thrust of SRM) reduction required to achieve the desired vectored thrust. The thrust reduction is proportional to the deflection angle.

The SRM provides a maximum thrust of 250 N and it weighs 53 kg (including 31 kg of propellent). Total lengh is 1500 mm and maxium diameter 215 mm. It operates for approximately 300 s. The currently proposed TVC design weighs 7.5 kg (four independently driven actuation units supporting 4 flaps).

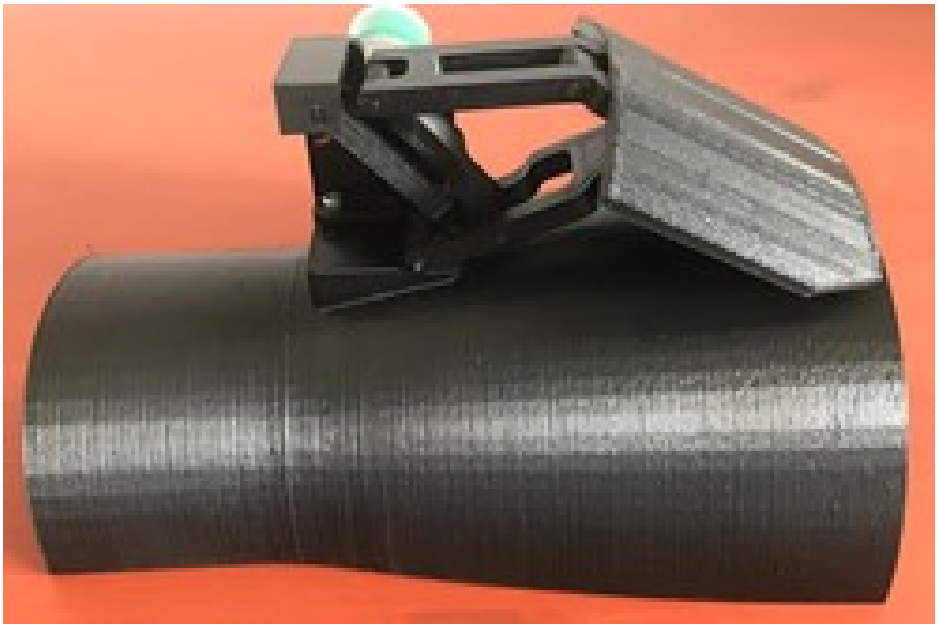

Figure 1. Thrust Vector Control mechanism – 3D printed prototype

Analysis

The complete analysis logic used for the purpose of TVC sizing is shown in Figure 2. In order to properly investigate the performance of the proposed concept, a set of analyses was prepared. Results obtained from CFD analysis helped to estimate the loads on the flap generated by the outflow of exhaust gases from the SRM. The dimension and location of a flap (its length, chamfer, radii and position with regards to the exit plane) was strictly related to CFD iterations. The most promising results from the CFD analysis served as an input for the next stage of analysis, namely the multibody simulation. This stage was aimed at calculating the torque of the electric motor required to overcome the aerodynamic loads, friction torque and inertia. The results dictated the size of the driving unit (stepper motor with planetary gearbox). The sizing task (motorization margin) was done in accordance with the ECSS standards and recommendations for margins to be applied and features to be taken into account [4]. The above-mentioned analyses showed the use of a COTS solution for the actuator unit would be acceptable.

The CFD analysis was the first and critical part of the mechanism design. At this stage, the optimization direction had be set and driving requirements needed to be frozen. In the scope of the project, the deflection angle was selected to be the driving parameter. However, it has to be noted that depending on the specific mission needs, the concept can be adjusted. During the CFD anaysis, 44 iterations of the flap were investigated. The effects of 6 variables associated with flap dimensions and position with regards to the SRM were examined. The interesting finding was that the flap insertion does affect not only plumb, as was expected, but also the flow inside the nozzle. The presence of the flap creates a set of shock waves. Those located close to the nozzle inner wall create a high pressure zone near the exit plane causing an additional lateral force component acting in the motor nozzle. This could positively influence the thrust deflection (similar behavior described in [3]).The additional component (even up to 15% of lateral force in the case of a flap with double curvature) interacts with the SRM directly – it does not load the flap, hence does not influence the actuator sizing (it does not enlarge the stepper motor which drives the mechanism).

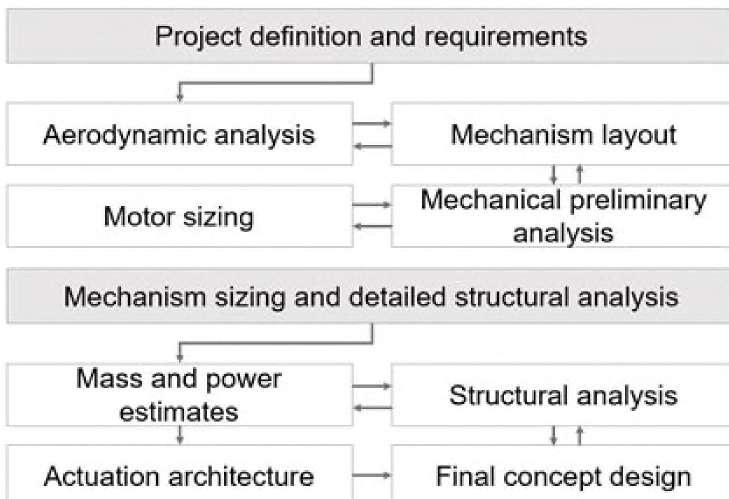

Figure 2. Analysis logic

Forces and torques coming from aerodynamic loads were a contribution for the next step of the analysis, the multibody analysis of the mechanism. The purpose of this analysis was to investigate and understand how the mechanism moves and operates under the influence of force (forward dynamic exercise). It allowed better understanding of the dynamics and kinematics of the variable ratio. Therefore, the analysis was a step towards motor sizing (motorization margin calculation in accordance with [4]). As a result of the multibody analysis, it was possible to obtain data used in motorization margin coming from:

- Aerodynamic loads,
- Friction,
- Inertia of the mechanism.

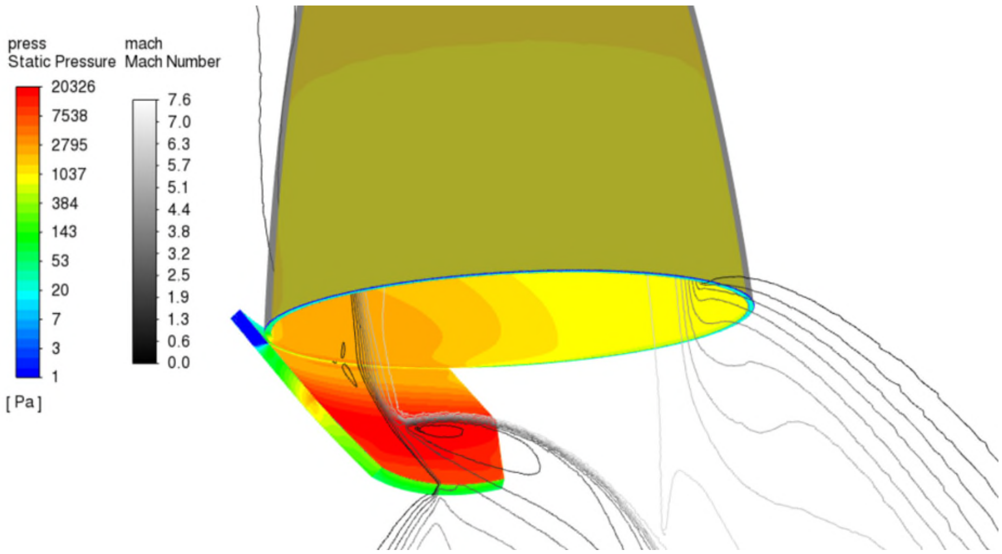

Figure 3. CFD results: static pressure and Mach number distribution around the flap

Based on the model prepared in MATLAB-Simscape, a stepper motor with an integrated low backlash planetary gearhead was chosen as best suiting the design requirements. The key reasons why this was considered adequate for the TVC application are:

- Long-term non-operational period in orbit in high vacuum favors a solution which is not using any brushed commutation;
- Control simplicity for a stepper motor allows for smaller, less complex driver than a brushless direct current motor;
- The relatively small diameter of the actuator comprised of a motor and gearhead under 43 mm allows to optimally use space around the SRM which is the baseline location for the actuators.

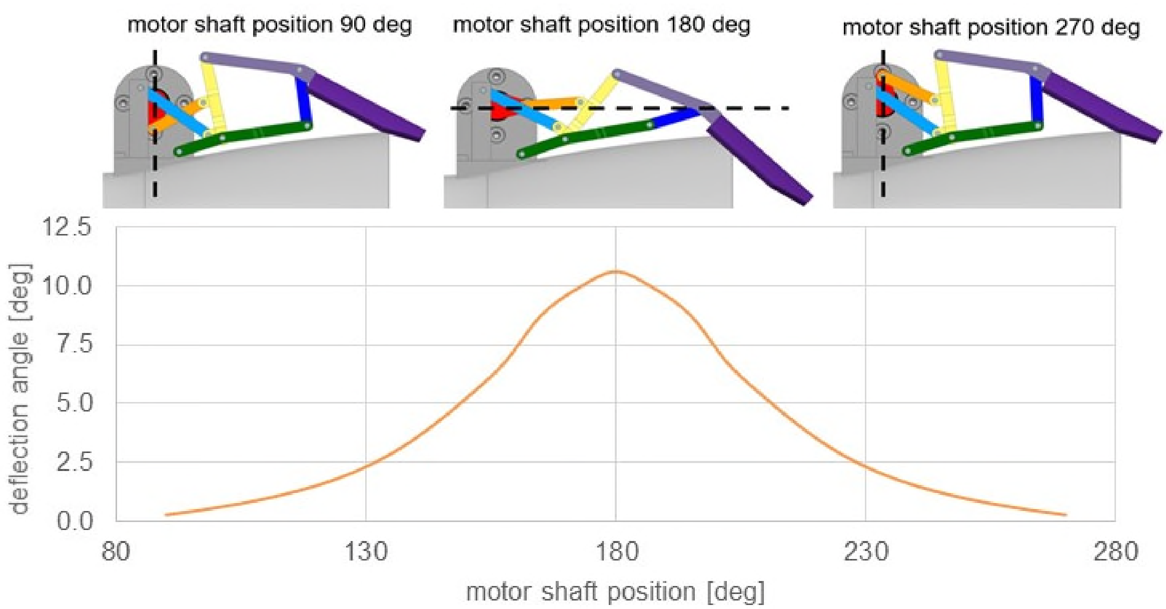

Figure 4. Flap insertion and thrust deflection angle with relation to motor shaft position

Ablation Tests

Ablations tests were conducted, considered to be one of the main elements of the overall test campaign. Based on the previous investigation, three materials were selected which seemed to be suitable for the application: tungsten copper alloy (W80Cu20), tantalum (Ta) and silicon nitride (Si_3N_4).

Tungsten-copper alloy was selected mainly due to the fact that it is also used for the throat insert in the SRM design. Having in mind the critical flow parameters, the throat area is exposed to more severe conditions than any other part of the motor in terms of temperature, pressure and erosion. Tests conducted as a part of the motor development project (30 seconds motor burn in atmospheric conditions) showed almost negligible erosion of the throat insert. However, the main disadvantage of W80Cu20 is its density. A material similar to tungsten-copper is tantalum – both in terms of thermal and erosion properties as well as in terms of density. The last candidate was silicon nitride – a ceramic that is characterized by low density, low erosion rate, and good thermal properties.

The ablation tests were conducted on a stand designed according to the standard ASTM E285-08 [5]. The test method determines the relative thermal insulation effectiveness when a squared specimen is placed in an environment of a steady flow of hot gas provided by an oxyacetylene burner. Hot combustion gases are directed along the normal to the sample. Each material was represented by 5 specimens which were flat, square panels with dimensions 101.6 +0.0/-0.71 mm wide and 6.35 ±0.41 mm thick. A thermocouple, aligned with the center of the torch tip, measured the back-face temperature of the sample. Due to the material properties of the candidates, the parameters and conditions described in the standard needed to be adjusted in order to get representative results. The heat flux described in the standard was too high – the temperature was rising too rapidly to allow the data acquisition system to collect usable information. Sampling frequency and thermal inertia of thermocouple were the main reasons for the adjustments. In order to extend the test time, it was decided to reduce the flow of gases and increase the distance between the torch tip and the specimen – both resulted in longer tests. The heat flux, measured before each test on a dedicated cold-wall calorimeter, was 340-380 W/cm^2, flow of oxygen was set to 23.9-25.0 liters/min, and acetylene 19.7–20.9 liters/min. Temperature was measured in range: ambient to ~660˚C.

In total 15 specimens were examined – one cracked during the test execution. Figure 5 shows the test results: W80Cu20 is the most promising in terms of thermal insulation properties, tantalum and silicon nitride show very similar behavior.

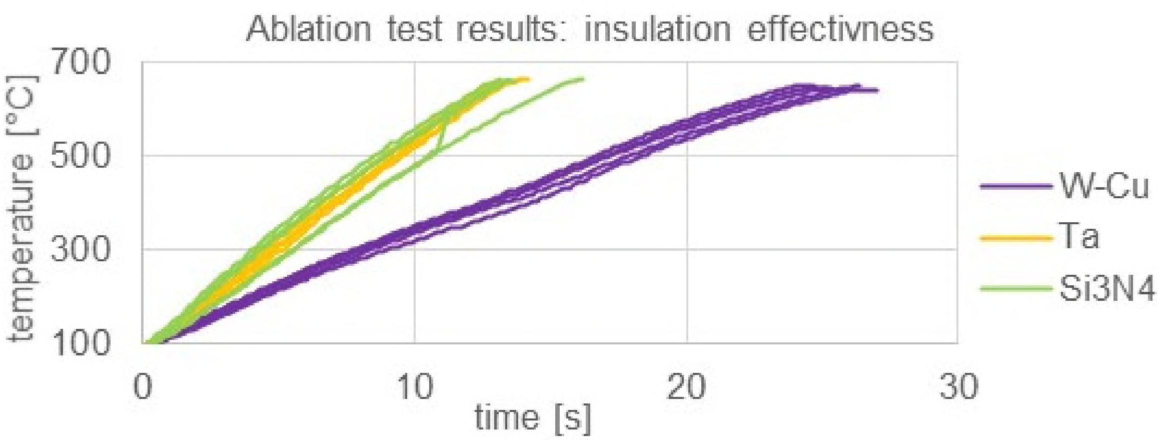

Figure 5. Ablation test results – insulation effectivness

One silicon nitride specimen was poorly manufactured – a bare-eye inspection showed some imperfections before the test. Polishing, as a part of the final sample preparation, probably helped to expose those imperfections which resulted in two spots. Despite the flaws, it was decided to still subject it to the evaluation. It cracked during the test. It occured most probably when the temperature at the back surface was around 500˚C. The thermocouple was destroyed. However, this sample showed how imperfections on ceramics might be severe in terms of results. Non-destructive inspection can be consided in order to investigate the quality of samples/components.

Specimens of silicon nitride did not bear any visual signs of the conducted tests. The samples before and after the tests looked almost the same (apart from the cracked sample). Whereas the W80Cu20 and Tantalum had circle-like shapes concentrated around the axis of the torch.

Figure 6. Ablation test stand and samples: silicon nitride (cracked), tantalum, tungsten-copper

The next tests intended to destroy the specimens, testing until burned-through is achieved. The heat flux, measured before each test, was 840-920 W/cm^2, flow of oxygen was 52.5-54.1 liters/min, and acetylene 43.2-44.7 liters/min. The first specimen tested was W80Cu20. However, after ~90 s of test, problems with the test stand occurred. Aluminum profiles of the stand, shields and water-cooling pipes started to fail. It was decided to stop the test for safety reasons. Similarly, but after ~60 s, the same happened with the Ta sample. Also those two materials started to melt. Melted metal drops, in orbit, could easily become space debris. Having that in mind, that the deorbitation system should not generate any additional debris in orbit, it is recommended to reconsider those options. A sample of silicon nitride cracked after ~8 s. In order to make sure it was not caused by material imperfections, 3 more samples were tested. All of them broke within 8-10 s in similar way: crack occurred vertically. It is believed that it was due to thermal expansion of the two steel mounting slots that held the sample during the test. Rapidly increasing the temperature caused dimensional change and as a result some extra compressive load was introduced which caused a crack. It is recommended to repeat the silicon nitride tests, but with a different sample mounting. In all cases, the back side of the sample reached the maximum temperature of the thermographic camera (~1500°C) before a crack happened.

Lessons Learned

Based on the current development of the project, the following conclusions can be drawn:

- Design driving requirements must be cleary defined at the beginning of the project – the Fowler mechanism with variable-ratio can be optimized precisely depending on the exact satellite needs and deorbiting requirements;
- The CFD anaysis showed that the selected method based on the outside flaps generates a reduction of thrust that is proportional to the deflection angle of exhaust gases;
- A well-optimized flap geometry is able to increase the thrust deflection by up to 15% by creating a high pressure zone, causing an additional lateral force component acting in the motor nozzle;
- W80Cu20 provided the best performance among the tested materials in terms of thermal insulation effectiveness, however, like tantalum, it melted on a test stand during the burn-through test. The deorbitation system should not generate any additional space debris, therefore, it is recommened to reconsider those materials. Silicon nitride cracks, most probably due to mounting frame thermal expansion – the test stand needs to be re-design and tests have to be repeated.

Conclusion

The most suitable method of thrust vectoring for a deorbitation propulsion system based on the SRM is a concept with outside flaps. The proposed mechanism, inspired by a Fowler mechanism used commonly in aviation to extend flaps on a wing, is a promising concept. The design introduces a number of benefits, i.e., relatively low envelop size, adjustable design (potential for optimization for different driving parameters) and necessity to actuate only flaps and associated levers (unlike a gimbal where entire motor needs to be moved).

Ablation tests were conducted for three candidates for the flap: tungsten copper alloy (W80Cu20), tantalum (Ta) and silicon nitride (Si_3N_4), with the first one having the best properties in terms of thermal effectivness. However, like Ta, it melts potentially causing a creation of new space debris (which shall be avoided). Ceramic material does not melt, but during tests, it breaks – probably due to thermal expansion of a holding frame. Tests need to be repeated on a different sample mounting.

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