SPACE DEBRIS BRAKING SYSTEM USING DERIVATIVE SRM FOR JUST-IN TIME COLLISION AVOIDANCE MANOEUVRE

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ABSTRACT

This paper presents the modelling methodology and the results of a feasibility study of a device for Just-In Time Collision Avoidance (JCA). The main principle of the proposed system is to generate a cloud intercepting the object trajectory and locally increasing the density, causing an aerodynamic drag force acting on the object itself. The debris, passing through the cloud, will experience a slight decrease of its orbital velocity, sufficient to result, after several revolutions, into a deviation from its nominal trajectory ensuring a safe reduction of any collision risk with other objects.

1 INTRODUCTION & CONTEXT

In order to limit the proliferation of space debris, several rules and regulations have been implemented. One of the main regulations is to deorbit a satellite in less than 25 years and to create no additional debris into orbit. In order to prevent collisions, the Joint Space Operations Center (JSpOC) transmits every day warnings to satellite operators. Using these warnings, operators can accurately monitor the hazardous pair of objects, foresee their potential crash more and more reliably and therefore get prepared to perform, if actually needed, collision avoidance manoeuvres. These manoeuvres can be performed only by operational satellites with operational propulsion capabilities. However, there are only 1381 active satellites in space with potential manoeuvre capabilities, compared to 17765 objects tracked by JSpOC (June 2016 values). There is therefore a strong need to find a way to avoid major collisions of space debris within a short schedule when propulsion is not available.

One possibility is Active Debris Removal (ADR). This approach consists in removing one or several objects previously known and defined. ADR is an orbital system that requires an orbital launch to the targeted orbit. The costs of such systems are high therefore they are dedicated to the most massive satellites with the highest product mass and collision probabilities [1]. The launch of this kind of vehicles also requires a planned mission far in advance with the management of re-entry risks.

Another possibility is to modify the trajectory of a risky object by an external means, just few hours or days before the expected collision. This modification of trajectory "just-in-time" will slightly modify the trajectory of the object in order to significantly reduce the threat and avoid a catastrophic collision.

The principle of Just-In Time Collision Avoidance (JCA) is to prevent impacts in Low Earth Orbit (LEO) by deflecting the orbit of inert objects without any direct interaction. The "just-in-time" trajectory modification is produced through an external means supposed to slightly change the orbital parameters of space debris in order to have, after several revolutions, a sufficient safety distance between the treated objects. To provide this slight change, a deltaV of only few centimeters/second (cm/s) is required. Indeed, the deltaV required to get an avoidance gap of 5km between the two objects considering a change of perigee of 1 km in a time delay of 24 hours, is around 2 cm/s. This level of deltaV required makes possible a responsive system launched from the ground.

2 PROPOSED SYSTEM

2.1 Principle

The principle of the proposed system is to generate a cloud intercepting the object trajectory. This cloud will locally increase the density causing an aerodynamic drag force acting on the object itself. The debris passing through the cloud will thus experience a slight decrease of its orbital velocity sufficient to have, after several revolutions a consistent deviation from its nominal trajectory. This ensures a safe reduction of the collision risk with other objects. Such a trajectory modification can be made by a system boarded in a responsive sounding rocket. The use of a responsive sounding rocket allows a very low cost launch compared to orbital launches ; it also has the advantages of an important reactivity and potential worldwide deployment. Several cloud generation technologies have been studied [2] [3]. This paper is focused on a specific technology that consists in using a Solid Rocket Motor (SRM) to generate a cloud of gas and particles.

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This study especially focuses on the calculation of the local density and the braking deltaV that can be provided by such a system. The principle adopted in this study is to put a SRM reversed at the top of a sounding rocket. The sounding rocket will culminate to an altitude close -but slightly lower - to the altitude of the targeted debris, to avoid any additional collision risk. The sounding rocket will have a suborbital trajectory and so, no debris or element of the system will remain in space after the operation. The ignition of the SRM at the apogee of the orbit will generate a cloud of gas and alumina particles. The debris will then penetrate into this cloud and undergo a very slight braking while encountering gas and particles across the cloud as depicted on Fig. 1.

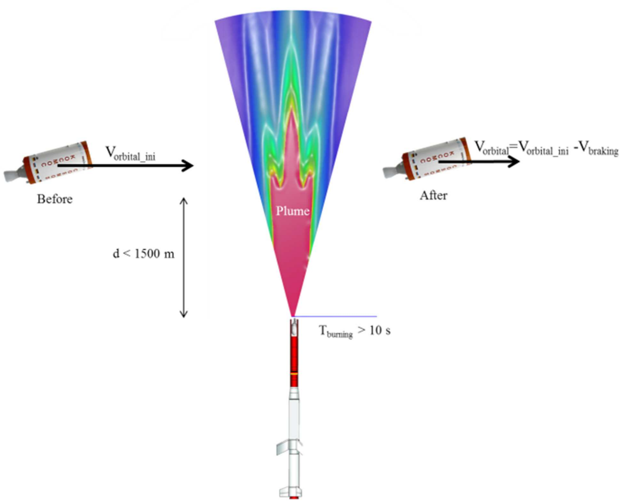

Figure 1. Schematic effect of the system studied

The consequence onto the debris of crossing the cloud is to lower its perigee altitude and to modify its orbital period. These slight changes will be propagated during several orbits before the moment of the dreaded impact, and thus suffice to reach the minimum safety distance required between the two objects. The earlier the alert will be given, the more efficient the system will be.

2.2 Study case

The objective of this study is to evaluate the braking capability of a cloud generated by a SRM. The reference case considered is based on a STAR-48 SRM type motor [4]. Different alternative configurations around this reference case have been evaluated to provide the sensitivities on the main parameters and to identify potential more attractive configurations. Indeed, since an SRM has initially been designed for propulsive features, it would be possible to alter its nozzle or operating conditions for example, to get an outcome more adapted to its diverted goal: producing a dense but not destructive cloud for braking purpose.

NB: With a small mature (on a Technonolgy Readiness Level point of view) SRM, it is very unlikely to have a median diameter higher than 10 µm; therefore there is no risk to produce particles reaching 100 µm in size, which is a really safe threshold value to avoid unwanted destructive impact.

3 MODELLING

Evaluating the braking cloud generator capability of a SRM included several steps:

- Preliminary motor characteristics and choices
- Motor plume modelling & simulation
- Cloud density integration along trajectory

Cloud modelling, and trajectory definition respectively, use variable parameters, such as nozzle geometry, particles' diameters, chamber's pressure and temperature, resp. relative position and plane of debris and cloud.

A wide range of variation of these parameters have been explored automatically, in order to get an overview of deviation levels to expect depending on future choices and operational conditions. This also allows to measure and sort the parameters' effect on braking deltaV, and to find which configurations are the most promising for collision avoidance.

3.1 Cloud Modelling

The modelling of the plume diffusion was made using Bertin technologies' homemade multiphysics code CPS_C™. Modelling and High Performance Computing have been achieved with CPS_C since 1985 in various fields of Computational Fluids Dynamics, Thermals, Radiation, Combustion for space systems and many other applications.

A continuous jet of gas and alumina particles has been simulated with a diphasic Lagrangian solver, using an AUSM scheme (Advection Upstream Splitting Method), widely known and used for multiphasic flows. Gas/particles plume interaction (friction and heat exchange) has been modelled and compared to literature. The computation domain is a 12 km long and wide slice including the nozzle (whose shape may be varied), so as to evaluate the density on different regions.

The size of alumina particles was modelled using Hermsen model [5] [6] with a lognormal distribution. Median (and constant) diameters evaluated ranged from 1 to 25 µm, the reference case being a lognormal law with median diameter around 6 µm.

The simulations on the reference case have been validated by comparison with the plume structure of comparable SRM from literature [7]. Fig. 2 contrasts the results of the simulation (in the upper part, mean diameter of the particles, red points represent large particles) with a diphasic plume structure expected for a comparable SRM (bottom part).

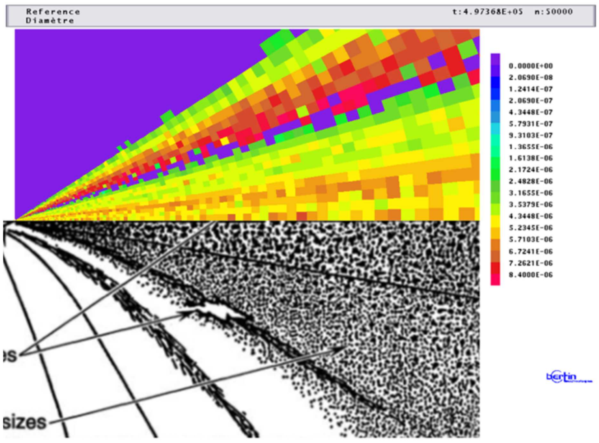

Figure 2. Comparison of SRM plume structure between CPS_C™ simulations (top) and literature (bottom)

On this figure, we can observe the conical structure of the particles plume, with different regions starting from the axis:

- A region of separation of alumina particles, by size, limited by a fringe where hot points formed "holes" without particles;
- A region without particles (in purple in fig. 2);
- Then, a region of large particles.

The association of the gas evenly spread in every direction and the particles gives the distribution of the mean density, at the origin of the braking effect, as represented on Fig. 3. This figure highlights the particular shape of the plume in vacuum on 3 km range.

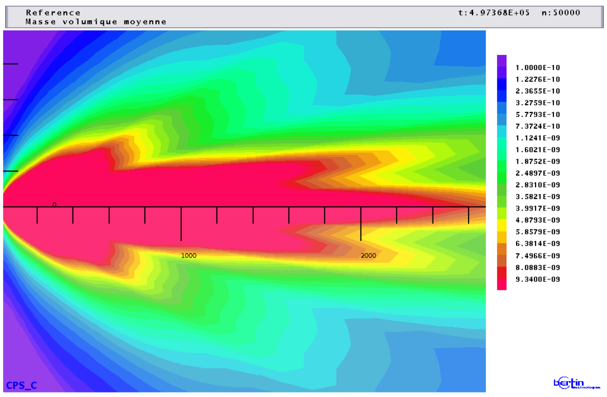

Figure 3. Distribution of the mean density of a SRM (display on 3 km)

Sensitivity of key parameters, such as nozzle geometry and interception configuration, has been assessed through an optimization approach.

3.2 Trajectory parametrization

As previously presented, the density is non homogenous. As a consequence, the trajectory will have a strong influence on the results. Best trajectories will be those that maximize the integral of density (Eq. 5).

In this study, a trajectory definition is characterized by three parameters as shown on Fig. 4:

- the parameter *d* is the distance in the orbital plane between the propeller and the trajectory of the debris,
- the parameter α is the angle in the orbital plane between the axis of the propeller and the trajectory of the debris, and
- the parameter *p* is the deviation from the orbital plane (parallel to the propeller axis).

This parametrization does not take into account all the possible trajectories but allows a better understanding of the influence of the trajectory parameters. This aims at giving a feasible envelop.

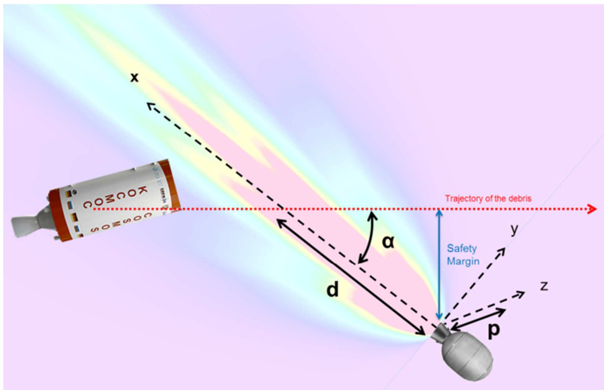

Figure 4. Parameters of the trajectory for deltaV calculations

Actually, all the possible trajectories are not operationally possible. For instance, it is not desirable to have the SRM at the same altitude as the debris (α=0 and p=0) in terms of risk managements. A constraint on the possible trajectory has so been added to take into account a safety distance required between the SRM and the debris. This constraint can be expressed as a minimum admissible angle β function of the distance *d*. To have a satisfactory trajectory, we must have:

$$\alpha > \beta \quad (1)$$

This criterion, presented on Fig 5, limits to a lower value the angle according to the distance. For instance, for a safety margin of 100 meters (red curve), at a distance of 500 meters, the angle could not be lower than about 11.3°.

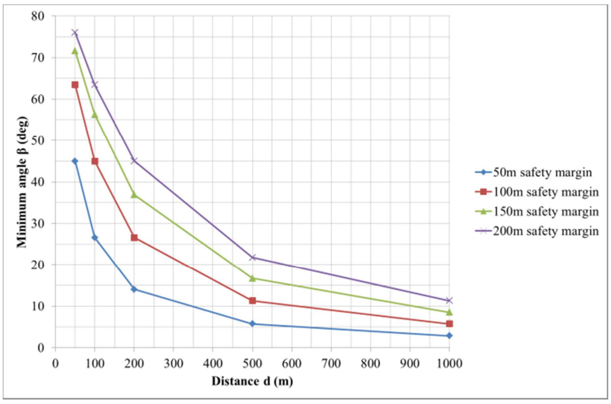

Figure 5. Minimum angle required to satisfy safety margin

3.3 Optimization

Dedicated post-treatment analyses were performed using an optimization approach to evaluate all the possible cases taking into account trajectory constraints. The CFD modelling allows obtaining the density of gas and particles on each point of the volume domain.

The fundamental principle of dynamics can be expressed for this application as follows:

$$M\frac{\partial v}{\partial t} = SC_x\frac{1}{2}\rho v_r^2 \quad (2)$$

With:

M, S and Cx being the debris' mass, reference aerodynamic surface and drag coefficient

ρ being the averaged local density

v_r being the relative velocity between the debris and the gas/particles of the plume

This equation can be simplified by considering the hypothesis:

$$v_r = constant = v_{debris} \quad (3)$$

$$\Delta v_{braking} \ll v \quad (4)$$

By combining Eq. 2, Eq. 3 and Eq. 4, it is possible to retrieve the expression of the braking deltaV via the formula:

$$\Delta v_{braking} = \frac{1}{M}SC_x\frac{1}{2}v\int_0^L \rho\delta x \quad (5)$$

Where v is the orbital velocity of the debris and $\Delta v_{braking}$ the braking velocity increment.

To calculate the braking deltaV ($\Delta v_{braking}$), a reference debris has been considered, a COSMOS-3M orbital debris, with the following characteristics:

- Mass (M) : 1360 kg
- S.Cx : 29.237
- Velocity (v) : 7451.832 m/s (circular orbit at 800km)

The parameter S.Cx represents an average value of the product of these two parameters based on several analyses of potential values of reference area and drag coefficient (depending on the debris' orientation relatively to the trajectory axis). The overall parameter $\frac{1}{M}SC_x\frac{1}{2}v$ is so a constant for the results presented after.

All the results presented in the next chapter consider this debris with these characteristics.

The objective of this study is to ensure to safely deviate the debris from its orbit. The optimization problem consists in finding a trajectory that maximizes the braking deltaV, and so to be able to rely on the plume action despite uncertainties.

For each set of motor parameters, the problem can be formulated as follows:

Maximize	$\Delta v_{braking}(z)$	(6)
With respect to	$z=\{d,\alpha,p\}$	(7)
Subject to	g_1: $\alpha>\beta$	(8)
	g_2: $\Delta v_{braking}>\Delta v_{braking_{\min}}$	(9)
	g_3: $d>d_{min}$	(10)

4 RESULTS

4.1 Reference case

This chapter presents the results on the reference case, considering a STAR-48 type SRM.

The braking deltaV achieved with the reference motor, a STAR-48 type, is presented on Fig. 6. The maximum deltaV achieved is approximately 3.5 cm/s for trajectories very close to the debris. For a trajectory with more operational safety, the maximum deltaV obtained is more on the order of magnitude of 2 cm/s.

These values comply with the requirement since with a braking deltaV of 2 cm/s, after 24 hours orbit propagation, the deviation of the altitude would be around 5 kilometers. Nevertheless, this value is merely at the requirement level and leaves no operational margins. This configuration, although possible, makes this system difficult to operate, as uncertainties at this stage of the project are important.

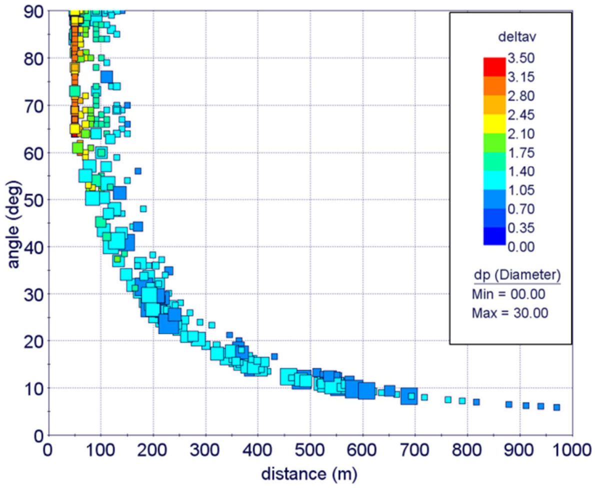

Figure 6. Braking deltaV for a STAR-48 type SRM function of the trajectory

The results presented on Fig. 6 provide a good overview of the impact of the distance (d) and the angle (α) onto the braking capability. The third parameter, the deviation around the orbital plane (its high values are shown by big squares, low values by small squares), is more difficult to interpret but also has an important influence. As seen on Fig. 7, the deviation from the orbital plane of the debris has rapidly an important impact on the results. Further than few tens of meters from the debris' orbital plane, the braking deltaV is too small to allow a sufficient braking of the debris. In consequence, the precision with the orbital plane of the debris should be as high as possible.

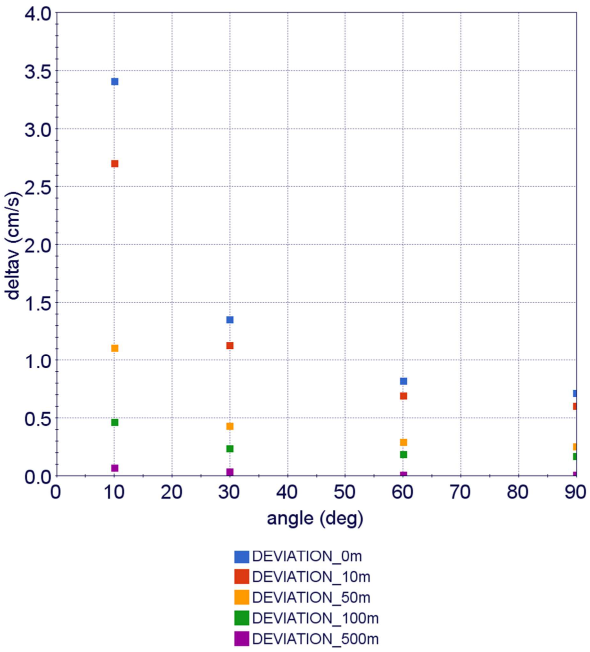

Figure 7. Impact on the deltaV of the deviation of the orbital plane for trajectories with an angle α of 30°

4.2 Sensitivity analyses

Sensitivity analyses have been performed to assess the influence of main parameters and to highlight potential interesting configurations.

To evaluate potential interesting architectures, sensitivity analyses have been led on several technical parameters of the motor such as temperature, pressure, propellant characteristics, geometry…

The braking capabilities of the system vary monotonically and non-linearly according to the size of the particles. This effect becomes quasi linear starting from few microns. The repartition law of the particles is on second order of magnitude, with only ten percent gain for a lognormal model of given median diameter compared to a model with a constant diameter of the same value. As the particles have a significant impact on the braking, their proportion is on first order of magnitude. The diminution of ejection speed is also an important parameter in favour of the increase of the deltaV; indeed slow particles are likely to be more widely expanded and closer together, causing a broad zone of higher density easing interception. As propulsive efficiency is not a criteria for this application, the nozzle doesn't need to be very efficient in that sense, therefore alternative geometries which may improve the efficiency of the braking system have been assessed. . These sensitivities revealed that it was possible to find more performant configurations.

Ultimately, mixing all conclusions of the sensitivity analysis altogether resulted in a particularly interesting configuration reaching a factor 10 on the braking deltaV compared to the reference case presented in §4.1. This level of braking capability appeared to be a feasible solution for an operational system and a potential way of investigations in the future. However, complementary works are needed to confirm these results on a realistic configuration.

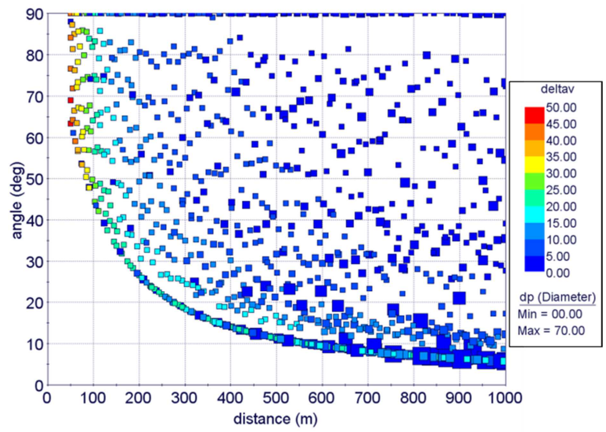

Figure 8. Results of a potential interesting configuration

5 CONCLUSIONS

A theoretical study has been carried out to assess the feasibility of a new concept for JCA by using a SRM.

This system appears to be feasible for certain motor configurations and relative debris trajectories. The distance *d* is an important parameter. The distance should be kept around some hundreds of meters to both maintain a sufficient level of braking and cope with a safety distance. The angle should be as low as reasonable in order to preserve a safety distance to the debris trajectory (requirement). The deviation from the orbital plane should be also as low as possible.

Quantitatively, the use of an off-the-shell SRM, in our case a STAR-48 type motor, conducts to a braking deltaV of a few cm/s. This makes the system feasible if the braking deltaV is provided at least 24 hours prior to the expected collision. However, the level of performance obtained with this system doesn't provide sufficient operational system margins. The sensitivity analyses have highlighted more interesting configurations, able to reduce mission failure's risks and to improve the braking efficiency by a factor 10. These architectures will be better studied to assess the viability of such system for JCA application.

Future works will investigate these configurations in order to provide system level JCA design including manufacturing and operational constraints. Non-technical constraints also play an important role in the viability of the system. Particularly, the safety policy will strongly influence the admissible trajectories and therefore the level of performance of the system.

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