A tool for risk assessment after a catastrophic event during suborbital flight operations

Giulio Avanzini[1a,*], Giovanni Curiazio[2b], Lorenzo Vampo[2c]

[1] Department of Engineering for Innovation, University of Salento, Campus Ecotekne (Building "O"), Via per Monteroni, 73100 Lecce (Italy)

[2] Course in Engineering of Aerospace Systems, Politecnico di Bari (Centro Magna Grecia), Via del Turismo, 74123 Taranto (Italy)

[a]giulio.avanzini@unisalento.it, [b]g.curiazio@studenti.poliba.it, [c]l.vampo@studenti.poliba.it

Keywords: Suborbital Flight; Risk Analysis; Space Flight Boundaries

Abstract. Suborbital flights represent a new frontier for the aerospace industry. Together with technological challenges and legal aspects, suitable tools for risk analysis are required to evaluate the potential damage produced by a catastrophic event during a suborbital flight. In particular, an explosion during the powered acceleration phase can cause dispersion of a large number of debris over a wide area, potentially harming the population living close to the launch site. A tool for the determination of the impact footprint of debris after an explosion is proposed, with the objective of supporting the definition of suitable ascent trajectories which reduce the risk for third parties below a publicly acceptable threshold. Legal aspects are also discussed.

Introduction

Suborbital flight is being envisaged as a new market for space tourism and as a means for low-cost accessto microgravity environment (although for time intervals limited to a few minutes). Safety issues are a primary concern for full commercial development of this novel class of activities at the threshold between atmospheric and space flight. This is relevant not only for people on board of the suborbital vehicle, butalso for third parties on the ground. Vehicle reliability should be high enough for commercial operations, with a risk level adequate for public acceptance. Simultaneously, tools are needed for evaluating the riskof third parties exposed to the passage of this novel class of vehicles in case of a (hopefully unlikely, but not impossible) catastrophic event. In this respect, also legal aspects require to be taken into due consideration, possibly requiring *ad hoc* regulations defined at a national as well as international level. During the descent phase, suborbital ballistic flight is less critical than conventional re-entry trajecto- ries. Assume as a reference the configuration of Space Ship II, developed by Virgin Galctic: after release from its mother-plane, the vehicle accelerates by means of a solid-fuel rocket, reaching its apogee in proximity of the Kármán line at 100 km with a velocity close to zero. Thermal loads and peak values ofdeceleration during descent remain within bounds which does not require a heat shield, nor it producesextreme structural loads. This makes the possibility of a major catastrophic event with vehicle fragmentation less likely during this phase. Conversely, failure of the solid rocket during the ascent may result into an explosion, with vehicle fragments impacting the ground on a large area. This implies that a risk analysis for third parties on the ground requires evaluating the impact footprint of debris produced by an explosion at different points along the trajectory.

The objective of the present paper is focused on this latter issue. Several potential explosion pointsare evaluated along the trajectory. A cloud of fragments and velocity increments along tangential, normal to the trajectory, in the vertical plane, and transverse directions are randomly generated. A correction is applied, in order to enforce that the total linear momentum after the explosion equals the momentumof the vehicle at the instant before the explosion. The magnitude

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 license. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under license by Materials Research Forum LLC.

of the increments is then scaled in order to match an estimate of the kinetic energy increase due to the energy released by the explosion. This energy is higher, at early stages of the ascent trajectory, when more unburned fuel is present in therocket, decreasing close to zero at rocket burnout. Stemming from previous experience with risk analysisfor remotely piloted vehicle operations over inhabited areas [1], statistical properties of impact footprintsin terms of number of fragments per unit area and kilograms of debris per unit area are determined, together with the distance of the centroid of the footprint. Combining this information with population density in the areas possibly interested by the fallout allows one to evaluate the risk for communities and individuals in the region, making it possible to design the ascent trajectory in such a way that the probability of damage to people on the ground remains within acceptable levels.

Legal aspects

Before the end of World War II, technologies developed for long-range bomber aircraft were paving theway towards the blossomong of commercial flight. At the same time it was clear that a supranational setof regulations was required for the sake of harmonization of flight procedures, aircraft certification andcrew licensing, together with other activities essential for civil commercial flight. The Convention on International Civil Aviation, usually referred to as the Chicago Convention, signed in 1944, features asmany as 19 Annexes, covering issues from meteorology to accident investigation, from aircraft noise endengine emissions to safety and secutiry aspects. Although other Conventions followed, such as the Con-vention on Offences and Certain Other Acts Committed on Board Aircraft in 1963 (known as the TokyoConvention), The Hague Hijacking Convention (formally the Convention for the Suppression of Unlaw-ful Seizure of Aircraft), signed in 1970, and The Montreal Convention (formally, the Convention for theUnification of Certain Rules for International Carriage by Air) signed in 1999, the Chicago Convention,updated in 2006, is still the backbone of international regulations for Civil Aviation.

Unfortunately, such an effort for providing an internationally recognized set of regulations for spaceactivities has yet to be undertaken. The Outer Space Treaty, signed in 1967 [3], is an early attempt, formally accepted by all Nations with relevant space activities, which states only basic principles, such as the freedom for all Nations to access space or the impossibility to claim portion of space under a single Nation sovereignty. Coming to more specificand technically relevant issues, there is no set of space rules, which can be the counterpart of the Rules of the Air listed in Annex 2 of the Chicago Convention. As an example, the United Nations delivered guidelines for the mitigation of the danger related to the increasing number of space debris [4], but these guidelines only provide a set of non-binding recommendations, without any actualconstraints (let alone, sanctions) for potentially dangerous space activities of sovereign states.

There are two major aspects that pose a serious obstacle to the development of a supranational spacelaw. First of all, the concept of airspace extends the sovereignty of a state to the volume where aeronautical activities are carried out above its territory and an airplane can follow a trajectory which avoids theairspace of war zones, as it is currently happening over Ukraine. This is not possible in space, where or-bits follow a prescribed pattern due to gravity and perturbing forces, and a continuous trajectory controlis not available. Hence it is impossible to prescribe boundaries in space which follow in any form thosepresent on the Earth surface and extended vertically for conventional air operations. A second issue is represented by the definition of an unambiguous threshold for separating the domains of atmospheric and space flight. Conventionally, the Kármán line, placed at 100 km, is often adopted as the boundary that marks the entry into space flight, but air traffic never gets even close to those altitudes, most air activities being limited to altitudes well below 30 km. Conversely, spacecraft orbit the Earth at an altitude higher than 250 km for avoiding a fast orbit decay. Conventional space vehicles rapidly cross the region between 30 and 250 km during launch and, much less frequently, reentry. The development ofsuborbital flight operation will soon require to adequately regulate activities taking place in the region of space between those used for conventional air and space operations.

Model for explosion, fragmentation and fallout

Among many other aspects, tools for risk analysis are required in order to define safe operations which do not result into a hazard for communities living in the neighborhood of the spaceport. This requires the identification of an impact footprint of debris in case of a catastrophic event that causes the fragmentation of the vehicle during the powered ascent trajectory. Flight data for Virgin Galactic SpaceShip 2 were used as a reference, which allow for the determination of suitable initial conditions in terms of vehicle speed and climb rate at different altitudes.

At the time of the catastrophic event, t_0, the velocity components of the vehicle are equal to $V_{x,0} = V_0 \cos \gamma_0$, $V_{y,0} = 0$, and $V_{z,0} = V_0 \sin \gamma_0$, with $\sin \gamma_0 = \dot{h}/V_0$. We assume that the explosion generates a cloud of N fragments. A uniform distribution of N random numbers r_k between 0 and 1 is generated. Assuming a vehicle mass of approximately $M = 4535$ kg and letting $R = \sum_{k=1}^{N} r_k$ and $f = M/R$, the mass of the k-th fragment is $m_k = f\, r_k$. Three sets of N Gaussian distributed velocity increments $\Delta v_{x,k}$, $\Delta v_{y,k}$, and $\Delta v_{z,k}$, are also generated. Provided that the momentum of fragments after t_0 must equate vehicle momentum right before t_0, three corrections, $\Delta v_{x,C}$, $\Delta v_{y,C}$, and $\Delta v_{z,C}$ are introduced, which satisfy the relation

$$\sum_{k=1}^{N} m_k(\Delta v_{x.k} + \Delta v_{x,C}) = 0\ ;\ \sum_{k=1}^{N} m_k(\Delta v_{y.k} + \Delta v_{y,C}) = 0\ ;\ \sum_{k=1}^{N} m_k(\Delta v_{z.k} + \Delta v_{z,C}) = 0$$

Velocity increments are then multiplied by a factor K_E, related to the intensity of the explosion, higher, when more unburned fuel is present in the rocket, and smaller at engine shut off. Assuming anexplosion intensity proportional to kinetic energy increase, K_E is obtained solving

$$\sum_{k=1}^{N} \mathcal{E}_k - \mathcal{E}_0 = \Delta \mathcal{E}_{expl}$$

where ΔE_{expl} is the increment of kinetic energy due to the explosion, $E_0 = ½ M V_0^2$ is the kinetic energy of the vehicle just before t_0 and the kinetic energy of the k-th fragment after t_0 is

$$\mathcal{E}_k = \frac{1}{2} m_k \left\{ \left[V_{x,0} + K_{\mathcal{E}}(\Delta v_{x.k} + \Delta v_{x,C})\right]^2 + \left[K_{\mathcal{E}}(\Delta v_{y.k} + \Delta v_{y,C})\right]^2 + \left[V_{z,0} + K_{\mathcal{E}}(\Delta v_{z.k} + \Delta v_{z,C})\right]^2 \right\}$$

A simple ballistic trajectory is assumed after the explosion. This allows to analytically determine thetime of impact on the ground of the k-th fragment, $t_{k,F}$, from the equation

$$h_0 + \left[V_{z,0} + K_{\mathcal{E}}(\Delta v_{z.k} + \Delta v_{z,C})\right] t_{k,F} - \frac{1}{2} g t_{k,F}^2 = 0$$

The distance flown in the along track and cross track directions are thus respectively equal to

$$x = \left[V_{x,0} + K_{\mathcal{E}}(\Delta v_{x.k} + \Delta v_{x,C})\right] t_{k,F}\ ;\ \ y = \left[V_{y,0} + K_{\mathcal{E}}(\Delta v_{y.k} + \Delta v_{y,C})\right] t_{k,F}$$

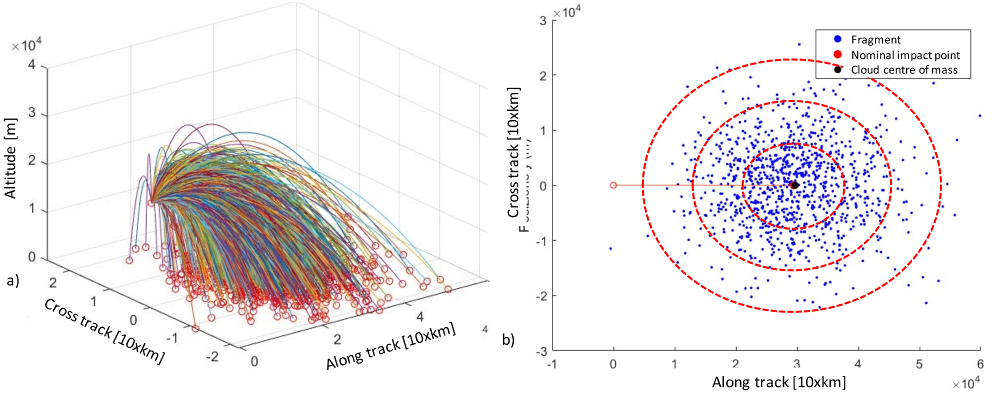

Figure 1. Fragment impact footprint: trajectories (a) and 3 − σ ellipses (b).

Results

The last equations are used for the determination of the impact footprint of the N fragments, when they hit the ground. Figures 1.a and b represent the parabolic trajectory and the impact footprint after a fragmentation due to an explosion at an altitude of 21 640 m, after 20 s from rocket engine ignition. In this preliminary analysis only the position of the fragments at impact is considered, neglecting the effects of aerodynamic drag on the resulting trajectory (hence also wind and turbulence). Regardless of these simplifying assumptions, it is possible to determine the standard deviation σ_x and σ_y in the along-track and cross-track directions of the positions of impact points with respect to the nominal point, represented by the impact point of the center of mass of the fragment cloud. The relevant data for a bivariate Gaussian distribution become thus available, which represents the possibility of the impact of a fragment in a given area. As it was done in [1], the three ellipses with 1σ, 2σ, and 3σ semiaxes contain 39%, 87%, and 99% of the fragments, respectively. These allows one to estimate the number of fragments per unit area expected to fall in each circular region. By matching these data with population density it is possible to derive the probability of hitting somebody on the ground. Future studies will address the effect of aerodynamic drag, wind and turbulence on the dispersion of the fragments. Moreover, together with the number of fragments per unit area, other risk parameters will be evaluated, such as the mass of debris per unit area and the kinetic energy of the fragments at impact, which are significantly affected by the deceleration due to drag.

Conclusions

A procedure for the determination of the impact footprint of fragments generated by the explosion of a suborbital vehicle during its powered ascent phase is outlined and some preliminary results proposed. Once the altitude and velocity profile of the mission are known, it is possible to perform a statistical analysis of the expected impact points of a cloud of debris, thus identifying the number of fragments per unit area expected to fall on the ground after a catastrophic event at a given altitude.

References

[1] G. Avanzini, D.S. Martí nez, Risk assessment in mission planning of uninhabited aerial vehicles, Proc. I.Mech.E. Part G: J. Aerosp. Eng., 233:10 (2019) 3499-3518. https://doi.org/10.1177/0954410018811196

[2] Various Authors, Convention on International Civil Aviation, Doc. 7300/9, 9th edition, Interna- tional Civil Aviation Organization, 2006

[3] Various Authors, Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, United Nations Office for Disarmament Affairs, 1967

[4] Various Authors, Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, United Nations Office for Outer Space Affairs, 2010