Vented Airbags: a new promising technology for Mars landers

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1. ABSTRACT

Due to its strong expertise in descent and landing systems for aerospace applications, Aero Sekur is giving a strong contribution to the European robotic missions to Mars.

Within the main exploration program, ExoMars, Aero Sekur is actually responsible for the design, development and qualification of two of the most important mission subsystems: parachute and airbag.

In order to achieve the mission goal, a probe will be injected in the red planet atmosphere; after the hot entry phase, at around Mach 2, a supersonic parachute, an 11 m diameter Disc Gap Band type, will be deployed by means of a mortar, slowing down the capsule below Mach 0,8.

At that regime the first parachute will be released and the main parachute, a 25,5 m diameter Ringslot type, will be deployed by the first parachute itself.

Few seconds after the deployment of the main parachute the capsule front shield will be released.

Having decelerated the capsule below a velocity of 45 m/s, at an altitude of around 700 m above MOLA, the main parachute will be released and a set of truster, controlled by a dedicated RCS, will bring the capsule at zero velocity at 15 m above the planet surface.

At this point the lander will be released and the airbag will be inflated during the free fall.

An innovative airbag, vented type, will be used in order to absorb the energy of the lander at impact; the airbag has six chambers, each one having a venting valve, that will be opened during the impact phase, controlled by means of a dedicated avionic system.

The venting will avoid the lander rebound and the vent control system will put the lander to the rest in the correct attitude.

Several drop tests have been carried out under Aero Sekur responsibility, all successful, demonstrating the high performances of the vented airbag and the company capability in conducting design and manufacturing of this kind of equipment.

Also the parachute system was successfully tested in a dedicated wind tunnel, demonstrating the Aero Sekur knowledge in the aerodynamic decelerators.

2. LANDING SYSTEM

Several landing systems could be used to land on Mars, depending on mission requirements. The actual mission requirements call for a payload of max 600 kg weight. Impact velocities are specified as a maximum vertical velocity of 10 m/s and a maximum horizontal velocity of 3 m/s. This is combined with a requirement to consider slopes of up to 18° at a scale of 10 m. In addition, rock distributions based on the analysis of the Viking 1 landing site are specified. Landings under these conditions are required to impose accelerations on the payload of no more than 35 g.

The specified requirements well fit with airbag technology that allows having low landing system/payload mass ratio.

Within the frame of ExoMars mission, two airbag systems, non vented airbag and vented airbag, have been studied, designed and tested at breadboard level, in order to select the suitable one.

2.1 Non-Vented Airbag Functional Sequence

Once the Landing Platform (LP) has been cut away from the descent airbag is inflated and first touch to the ground will happen. The initial impact with the ground will dissipate some of the kinetic energy by a number of mechanisms including transfer to the inflation gas through thermodynamic irreversibility, to the fabric by hysteresis, and through interaction with the terrain via friction and compression of the regolith.

Any kinetic energy associated with tangential velocity may be transferred to rotational kinetic energy but this may be returned on a subsequent impact. As a result of the energy transfer, the rebound velocities are lower than the incident velocities and, unless the system is bouncing down a slope, the impact velocities for the second impact are lower. Further energy is dissipated on the second and subsequent bounces until the kinetic energy is reduced to zero and the Lander is at rest on the surface.

Before the LP petals are opened to allow rover egress the airbags must be deflated and retracted.

2.2 Non-Vented Airbag Design

The non-vented airbag system, shown in Fig. 1, consists of a set of four billiard rack airbags, with one attached to each side of the tetrahedral payload. All four airbags are geometrically the same but some differences in layout and interfaces. Each airbag consists of six lobes with a diameter of 2 m. The distance between centers is 1.35 m. The side airbags have a volume of 16.2 m^3, and the base airbag has a volume of 15.8 m^3, making a total volume of 64.4 m^3 when inflated to a differential pressure of 10.5 kPa.

Fig. 1. Non-vented airbag system

Each of the three side airbags are linked to the base airbag by a vent with an effective area of 0.085 m^2, assuming a discharge coefficient of 0.65, this results in a geometric area of 0.131 m^2.

2.3 Vented Airbag Functional Sequence

The expected initiation for the landing system is the acquisition of Mars terrain by a radar altimeter or similar device. At a predetermined altitude the restraint on the packed airbags is released and the inflation system inflates the airbags. The time at which the airbags are inflated is a trade between ensuring that they do not interfere with any necessary measurements or sequencing in the final stages of the descent, as plume of the attitude engines, and that they achieve full inflation and pressure prior to the first impact.

Once the Landing Platform (LP) has been cut away from the descent system it freefalls to the ground with the residual linear and rotational velocities inherited from the descent phase, accelerating under gravity. Atmospheric effects during the freefall are minimal at the impact velocities expected, due to the low dynamic pressures induced by the descent and any winds and the large mass and inertia of the system.

During the first impact with the ground all the kinetic energy associated with the velocity component vertical to the surface is transferred to the inflation gas. At the correct time the gas is vented to the atmosphere. Careful control of the timing is required to ensure the rotational dynamics of the payload are brought under control to avoid turnover. With the gas vented the LP is left with no further form of deceleration and freefalls the short distance (~0.35 m) to the ground with the residual horizontal velocity to slide across the terrain.

The main difference wrt non-vented system stay in energy dissipation: the vented system do not allow any rebounding, thereby can be designed to cover only one side of the Lander rather than all the faces, with a relevant mass system reduction.

2.4 Vented Airbag Design

The vented airbag system consists of an elliptic section approximation to a torus with a hexagonal planform as shown in Fig. 2. The elliptic section midway along one side of the hexagon has major and minor diameters of 1.6 m and 1.1 m respectively and the distance between the centrelines of the opposite sides of the hexagon at this location is 2.5 m. Each segment has a volume of 2.05 m^3 making a total airbag volume of 12.3 m^3 when inflated to a differential pressure of 9.6 KPa.

Each of the six sides of the hexagon is isolated from each other with internal bulkheads which restrict the flow of gas between the resulting six segments. The elliptic section of the segments is maintained away from the bulkheads by a series of cords running across the minor diameter of the ellipse.

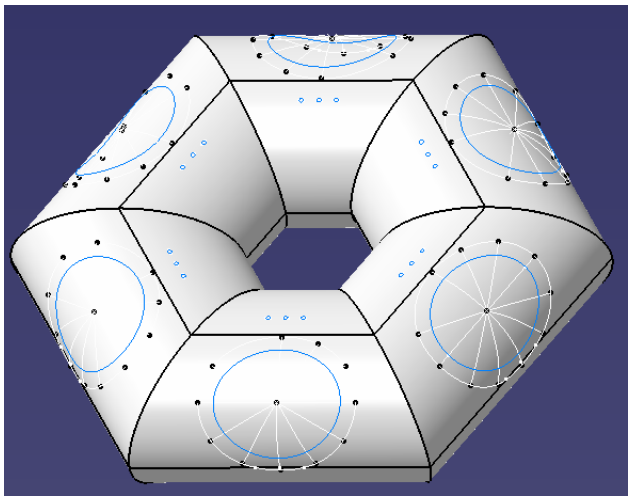

Fig. 2. Airbag system design

The six segments making up the airbag are connected to each of their neighbours by small orifices. Some reduction in peak pressure is attained with the introduction of these pneumatic connections. The size of the orifices cannot be too large as the differential loading, crucial to controlling the payload dynamics, is dependent on distribution of the deceleration loads around the LP. In addition, the differential venting of segments should not cause significant loss of pressure to unvented segments. An additional benefit of the inter segment connections is greater flexibility in the inflation system design and configuration.

Venting is achieved independently for each segment through a vent valve with an geometric area of 0.65 m^2, assuming that the discharge coefficient under Mars ambient conditions is 0.6, as measured after vent tests in vacuum chamber simulating nominal Mars pressure conditions.

The current baseline is to employ a petal type valve: the valve consists of a series of overlapping petals covering a circular orifice. Each of the petals has a loop attached at its apex and a single cord is run through these loops to hold the valve closed. By cutting this cord on demand, by means of a pyrocuttrer, the load bearing part of the valve is removed exposing the airbag pressure to the valve seal which is stowed beneath the petals. The sealing consists of a tube permanently bonded to the valve rim. The other end of the tube was laid flat and sealed with vacuum putty. When the valve is opened the tube is inflated and the sealed end is opened.

The time between the vent condition being detected by the onboard sensors and the opening of the valve shall be minimized. In particular it is estimated that the total delay due the electronic is 4 ms. Further, the time for valve to open shall be as small as possible. It is estimated, based on the vent test in vacuum chamber reported in [1], simulating the vent in nominal Mars pressure conditions, that after the triggering 8 ms are required for the pyro activation and 5 ms for the complete valve deployment and opening.

The vent control logic is based on the signal acquisition of 12 accelerometers (two dedicated to each segment of airbag for cold redundancy) installed on the Landing Platform (LP). The signals are integrated in order to obtain the velocity of the platform starting from known release conditions. The dynamical data acquired by the accelerometers are transmitted to a central unit that memorizes and process the acquired data.

The vent control algorithm takes into account only the vertical component of the acceleration, measured in the LP local coordinate system; an offset equal to Mars gravity will be given, since the accelerometer will be reset before the release of the landing system; the calculated acceleration is then integrated in order to obtain the velocity.

The velocity scaled Vent Control Algorithm (VCA) is based on the relation between the fire velocity and the maximum impact velocity, different for each segment of the airbag. The algorithm detect the maximum impact velocity (V_{max}) in real time for each segment and set the fire velocity as specified by the function binding these two values. The law that links the fire velocity and the max impact velocity is found varying, in case of flat landing, the max impact velocity and tuning the fire velocity on each case in order to stop the LP before hard impact with the ground. The law between max impact velocity and fire velocity is almost linear and given by Eq. 1.

$$V_f = 35\% \; V_{max} \qquad (1)$$

2.5 Drop Test Campaign

In the frame of ExoMars mission, in order to validate non-vented and vented airbag system, respectively one and three drop test campaigns were carried out. In particular, the last one was aimed to advance the level of maturity of the vented airbag by a swift but methodical increase in the severity of the impact conditions, to expand the known performance envelope of the system.

2.5.1 Non-Vented Airbag Test

The objective of the non-vented tests is essentially to verify that the payload is protected from the landing terrain while limiting the levels of loads transmitted into the structure under the different impact conditions. The most severe sever condition comes from terrain and rocks acting on the airbag that has to resist puncture.

The test campaign was carried out in CIRA facility, and 5 tests with increasing level of severity in landing conditions were performed. Test set up is shown in Fig. 3. The test campaign was successfully completed and did provide useful data to determine the damping available to the system on a variety of surfaces and for a variety of impact conditions and to quantify the rebound dynamics of the system for a variety of incident impact conditions. The non-vented airbag design was demonstrated to be compliant with Mars landing requirements.

	N° of Tests	Facility	Outcome
Non-vented test campaign	5	CIRA	Successful non-vented airbag technology validation

Table 1. Non-Vented airbag test campaigns summary

Fig. 3. Non-vented airbag test set-up (CIRA)

2.5.2 Vented Airbag Test Campaigns

The greatest risk associated with the vented airbag landing system is the possibility of tumble or turnover during the landing. This possibility is increased as lateral velocities, slopes and pitch angles increase for the landing, together with rock garden. In particular the effect of slopes, combined with the pitch attitude of the LP, on the landing dynamics and in particular their effect on vent sensing and logic has still to be investigated and tested. The planned tests had introduced slopes to the landing in a measured way so that its effect can be studied in detail in order to assess the effectiveness of the control system in place.

The test plan was devised in order to reproduce a representative part of the landing conditions envelope expected on Mars. By the way, because of the airbag physics, it is not possible to match, under Earth ambient conditions, the same Martian dynamic behaviour at impact. The test matrix tries only to reproduce part of the worst impact conditions on Mars.

It has to be said that the difference between Mars and Earth airbag system behaviour is due mainly to the different stiffness of the airbag at impact and, secondarily, to the different gravity acceleration. On Earth the airbag has to be inflated at a significantly lower differential pressure, compared to the Martian one, so that the reaction force acting on the LP at impact induces higher acceleration on the payload because of the increased footprint when the internal pressure increases significantly. Besides, because of the higher acceleration during airbag compression, the ABS dynamic is faster on Earth than on Mars, causing an amplification of possible imprecision in controlling the vent and of vent delay effect on post vent dynamics. Based on this consideration it is possible to assess that the test envelope is representative of Mars conditions for those aspect that can be reproduced in Earth ambient and conservative under other aspects.

Since the driver in airbag behaviour changes is the different pressurization, the matching has been focused on the inflation pressure of the airbag, considering the energy associated to the compression of the gas due to airbag volume reduction. From LS-Dyna analysis it is shown that the vent happens in average when the volume is reduced to 88%. As shown in Fig. 4, the equivalence between Mars and Earth happens at about 88% volume reduction if the airbag inflation pressure on Earth is 3.0 kPad.

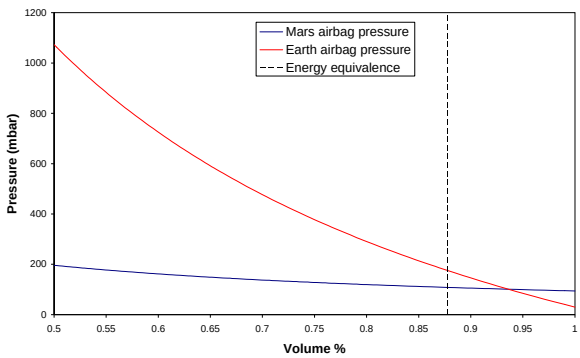

Fig. 4. Pressure trend with ABS volume reduction on Earth vs Mars

The first drop test campaign has been carried in CIRA facility, two more in Aero Sekur. The test article is shown in Fig. 5.

Fig. 5. Vented airbag test article and test set-up (Aero Sekur)

The LP mock-up is equipped with a vent control system is composed by seven peripheral unit (accelerometers and pressure sensor, one dedicated for each segment and one in CoG position without pressure sensor) and one central unit. The single peripheral unit is made up of 1 tri-axis accelerometer and 2 pressure sensors. The CoG unit is equipped with 3 rate gyros to measure the attitude of the LP.

The vented airbag, that finally was selected as mission baseline, was submitted to several test campaigns to validate each subsystem.

The first test campaign, carried out in CIRA facility, was aimed to validate the vented airbag concept and design. Seven tests were successfully carried out in presence of terrain slopes and rocks, with high lateral velocity at landing. A first model correlation was attempted and, based on simulation and test results, the accelerometer based vent control logic was selected as a baseline.

The following test campaigns were focused on the validation of the vent control algorithm. In particular four tests were aimed to validate the accelerometers based vent control logic, and six more tests were targeted to validate the vent control algorithm.

	N° of Tests	Facility	Outcome
Vented test campaign 1	7	CIRA	Successful vented airbag technology validation
Vented test campaign 2	4	Aero Sekur	Successful validation of accelerometer based vent control logic
Vented test campaign 3	6	Aero Sekur	Successful validation of

Table 2. Vented airbag test campaigns summary

Totally 17 tests were successfully carried out, and validated both the airbag system and the control logic.

Test results were useful to correlate the LS-Dyna model used to assess airbag performances in Mars environment. The objective of the correlation is to increase reliability associated with the FE Model used to evaluate airbag performances in Mars environment by correlating test acquired data with test prediction and eventually tune the model. The correlation logic is in accordance with the functional sequence of the airbag system. The LS-Dyna simulation is carried out including all the initial conditions, and setting firing sequence as acquired during the test. As an example, the comparison between test results and LS-Dyna results, is showed. The test initial conditions are shown in Fig. 6. Fig. 7 shows acceleration and velocity at LP CoG from test vs LS-Dyna results. The acceleration trend shows a very good correlation during cushioning; the max acceleration is 22.5 g from test and 22.6 g from LS-Dyna simulation. The LS-Dyna model correlation shows very good results even in terms inertial behaviour, as highlighted by the free fall time after vent. The difference in the second acceleration peak is due to the terrain and LP stiffness, both modelled as rigid body in LS-Dyna code; only fictitious contact stiffness is introduced in the model, but the acceleration level is not relevant.

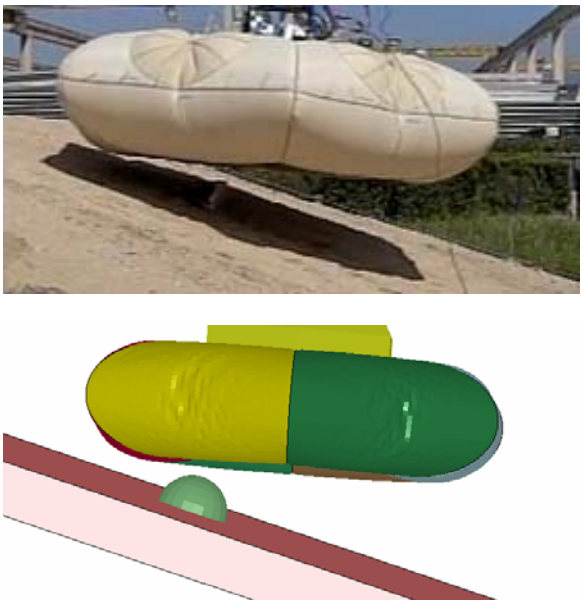

Fig. 6. Example of impact conditions; test vs simulation

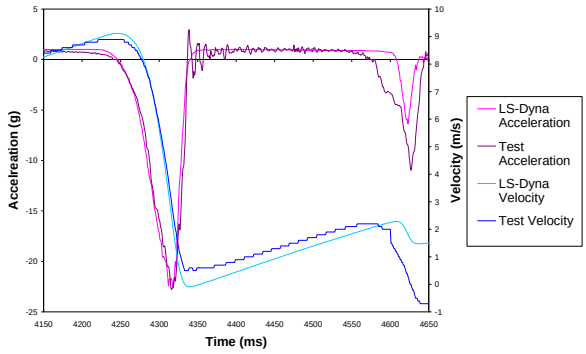

Fig. 7. Acceleration and velocity at LP CoG: test vs LS-Dyna

3. CONCLUSIONS

Several airbag drop test campaign were carried out successfully and allowed the selection of a suitable landing system for ExoMars mission.

The vented airbag, selected as baseline, was widely tested by introducing as much as possible different landing parameters during the test to prove vent control logic efficiency in presence of severe landing conditions. The vented airbag was demonstrated to be effective in several conditions both in terms of airbag technology and design and in terms of control logic. In particular the airbag is was demonstrated to be capable of preventing the LP overturn and limiting the acceleration on the payload as per specification. Moreover test results were used to correlate airbag FE model successfully.

In order to reach TRL 5 for vented airbag technology, drop test in Mars simulated ambient pressure. Foreseen tests will be performed in Large Solar Simulator in ESTEC.

4. REFERENCES

1. Ciambottini D., Giovangrossi G., Vacuum Inflation/Deflation and Drop Tests for the Development of ExoMars Airbag, *3rd International Workshop on Verification and Testing of Space Systems*, Torino, Italy, 2009.