Analysis of landing mission phases for robotic exploration on phobos mar's moon

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Abstract. Landing phase is one of the crucial and most important phases during robotic aerospace explorations. It concerns the impact of the landing module of a spacecraft on a celestial body. Risks and uncertainties of landing are mainly due to the morphology of the surface, the possible presence of rocks and other obstacles or subsidence. The present work quotes results of a computational analysis direct to investigate the stability during the landing phase of a lander on Phobos, a Mars Moon. The present study makes use of available software tools for the simulation analyses and results processing. Due to the nature of the system under consideration (i.e., large displacements and interaction between several systems), multibody simulations were performed to analyze the lander's behavior after the impact with the celestial body. The landing scenario was chosen as a result of a DOE (Design of Experiments) analysis in terms of lander velocity and position, or ground slope. In order to verify the reliability of the present multibody methodology for this particular aerospace issue, two different software tools were employed in order to emphasize two different ways to simulate the crash-box, a particular component of the system used to cushion the impact. The results show the most important frames of the simulations so as to provide a general idea about how lander behaves in its descent and some trends of the main characteristics of the system. In conclusion, the success of the approach is demonstrated by highlighting that the results (crash-box shortening trend and lander's kinetic energy) are comparable between the two tools and that the stability is ensured.

Keywords: landing stability; DOE analysis; crash-box; multibody simulation

1. Introduction

In the last 40 years, many robotic explorations were coordinated by the most popular aerospace companies: for example, Viking 1 in 1975 by NASA (the results of which are shown by Briggs *et al*. 1977 and Carr *et al*. 1977); Venera 13 in 1982 by the Russian space agency (which made possible to study the composition of rocks on Venus, as described by Surkov *et al*. 1982); Near Earth Asteroid Rendezvous in 2001 by NASA (Acuña *et al*. 1997, described this mission, which concerns about the study of 433 Eros, a near-Earth asteroid, and Miller *et al*. (2002) showed the results); Hayabusa in 2003 by JAXA, (which was the first sample return mission, as described by

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Kubota *et al*. 2006); Rosetta in 2004 by ESA (which purpose is clearly explained by Glassmeier *et al*. 2007). Galeev *et al*. (1996) have shown and described a new mission called Phobos Sample Return, which start is planned for 2025: the main goal of this robotic mission is to take a sample from the Phobos, one of the two Mars' moons, and return it to the Earth. There are also secondary goals, like a global analysis about the other Mars' moon, Deimos. Phobos is the innermost and larger of the two natural satellites of Mars, the other being Deimos and has a mean radius of 11 km. Fig. 1 shows Phobos, between Mars and Deimos:

Fig. 1 The illustration shows, from the left, Mars, Phobos and Deimos

One of the crucial points of the overall mission is the landing phase on Phobos: the case study is represented by the analysis of the landing gear stability on the Phobos surface. In this context, the main problem is the presence of a very low gravity (more than 3000 times lower than the Earth one), which could cause some bounces of the lander after the impact on the Phobos surface. This issue is common between almost all aerospace robotic missions, and many solutions are present in literature (e.g., "pinpoint landing" is showed by Chu 2006 and Steinfeldt *et al*. 2010). The solution presented by this paper regards the ignition of thrusters to push the lander on the surface. Hofer *et al*. (2006) show the working of thrusters, which are used for several aerospace missions, especially to control the position of the spacecraft during his flight. Thruster cannot be turned on to control the lander descent, because the debris released by those thrusters could contaminate the surface, derailing the overall mission. Essentially, the lander is in a free downfall condition. Furthermore, there is no knowledge about the morphology composition of the surface, so there could be some dangers or slopes. Stability analyses proposed in the present paper are performed in the worst case scenario, chosen as a result of a DOE (Design of Experiments) analysis. In this analysis, the most characterizing parameters are varied to find which of their values lead to the worst scenario possible, which the lander could have to land in.

The aim of these activities is to minimize risks caused by this maneuver, which could otherwise ruin the overall mission. The way to achieve this result is to simulate the lander behavior during his descent and the type of the simulation adopted is the multibody one. The MBS (MultiBody Simulation) methodology represents a very good trade-off between mathematical complexity and accuracy. MBS methods have been successfully used to describe a real-world behavior of many systems encountered in a wide variety of industries such as transportation (automobiles, buses, trucks, trains and planes), industrial machinery (textile, packaging and manufacturing), aerospace systems (spacecraft and missiles), consumer goods (washing machines and watches) and electro-mechanical systems (printers and copiers). A defining characteristic of all these systems is that

they can undergo large overall motion that is comparable to their dimensions. About aerospace systems, the task of developing realistic computer simulations of motion of complicated aerospace vehicles has stimulated research in the field of multibody dynamics. Many multibody formalisms are currently available to the spacecraft analyst, as evidenced by the wide body of literature on this topic. For example, Hooker and Marguiles (1965), Hooker (1970) and Fleischer and Likins (1974) show the theory behind the multibody simulation for aerospace application, whereas Rosenthal and Sherman (1986) describe how Kane's method for multibody simulation helps to improve run-time performance and usability. Then, for this case study, a multibody model of the landing overall system (the lander and the ground, with some obstacles) was built. Of all the components of the system, particularly interesting is the crash-box one: this element, placed in the legs of the lander, cushion the impact by kinetic energy absorption. Commercial multibody software have not a body to simulate crash-box behavior, so it is needed to find a different way to do it. To validate this work more, two different ways (implemented in two different software) were adopted. The first way is co-simulation between a multibody software, Altair (1985) in this case, and a 1D Simulation tool, solidThinking Activate (1998), where the first calculates the crash-box stroke and the second the crash-box reaction force by a direct confrontation with its behavior trend, using the information from the multibody software; the second way is a mathematical function, directly implemented in the multibody software, MSC Adams (1963) in this work. Results show how, through the ignition of thruster as said before, lander stability is obtained in both methods of crash-box behavior simulation.

2. The lander model

In order to perform landing stability analyses, it was necessary to build a multibody model of the lander. The first step was to import in the multibody software the CAD file of the lander, which carries the geometric information of the system, like the shape, the inertia and the center of mass of the elements which define the overall mechanical system. Fig. 2 shows the geometry of the lander.
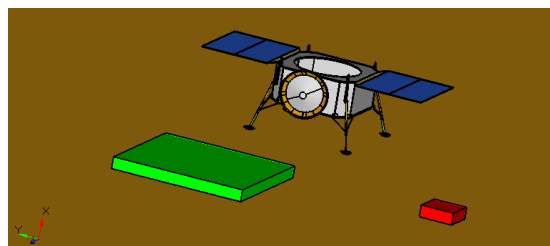

Fig. 2 Geometry of the overall system derived from CAD file

The landing module components are shown in Fig. 3. For the landing module (Fig. 3(a)) there are 2 solar arrays (in blue), 1 chassis (in green) and 4 legs (in red); for the leg of the lander (Fig. 2(b)), there are 2 side brackets (in light blue), 1 top tube (in green), 1 lower tube (in red) and 1 disk (in blue).

In addition of the lander, in Fig. 2 are shown geometries, in form of parallelepipeds, related to

two obstacles and to the ground, whose properties are added in the contact simulation with a value of the stiffness parameter equal to $10^4 \frac{N}{mm}$ and a value of the damping parameter equal to $1 \frac{N*s}{mm}$. It is important to note that, to make the graphic not heavy and achieve a greater clarity during simulations, only the lander graphic is represented, not the graphic of all the elements that really land (in fact all the equipment used to return the sample to the Earth is missing): however, inertial properties and the mass implemented consider the presence of all the elements that really land.

2.1 The crash-box model

The crash-box is a crushable element, which is used to absorb kinetic energy and to cushion the impact of the lander with the Phobos' surface. As described in the introduction, the crash-box behavior is simulated in two different ways: by a co-simulation with a 1D simulation software and by a mathematical function.

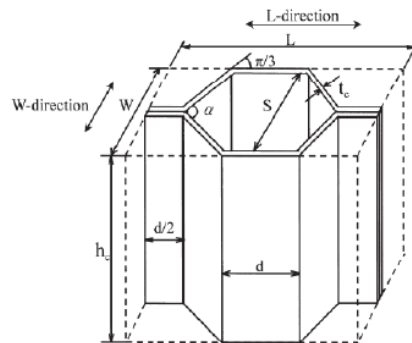The crash-box has a cylindrical shape and has a hexagonal metallic "honeycomb" cell, as shown in Fig. 4.

Fig. 4 The crash-box "honeycomb" cell

Shin *et al*. (2002) have studied the behavior of a square tube crash-box and its energy absorption capability. Although the crash-box of the application presented by this paper has a "honeycomb" structure, his behavior is similar: this "honeycomb" structure has the feature to collapse in a uniform and efficient way. It is very reliable and light, and for these reasons, it is appropriate for energy absorption applications. When the crash-box is subjected to a high enough compression load, the "honeycomb" structure goes to instability (a similar phenomenon to the peak load) and collapses. While collapsing, after a short stretch of elastic field, the crash-box goes on the plastic field: increasing the stroke, the absorbed force remains almost constant and there is no elastic recovery, due to the plastic field properties.

If there is no more absorbed force after the crash-box is in plastic field, the crash-box does not return to his original length, because the stroke of the collapsed portion is gone, as a result of the energy absorption.

In this analysis, it is not needed to simulate the crash-box geometry too, but just his behavior, hence the resistance (as a force) that it opposes to the sliding of the lower tube of the leg in the upper tube: when there is no contact between the lander leg and the ground, the crash-box does not

(a) Landing module   (b) Particular of one of the leg
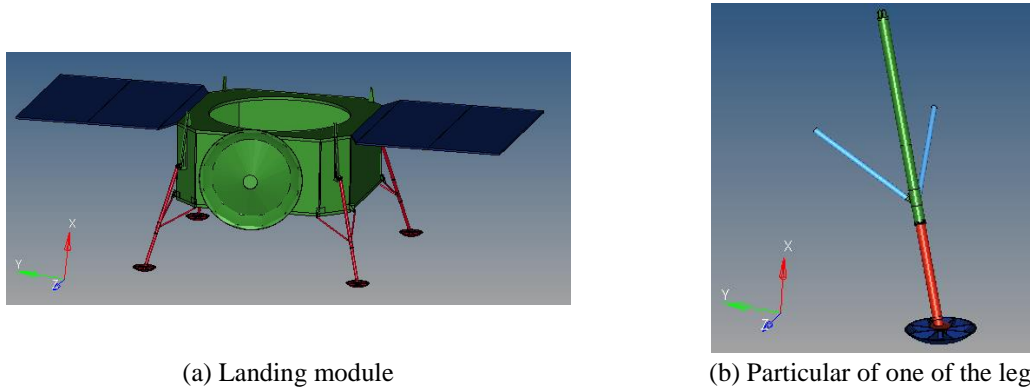
Fig. 3 The multibody model for the landing module

shorten, when there is contact and the contact force is over the limit value of the crash-box behavior, it starts collapsing, and so the simulation starts calculating the resistance force produced by the crash-box.

Moreover, the stroke is not recovered, because the crash-box is in plastic field, so the simulation has to store his value and have to keep it constant until there is another condition for which crash-box collapse, i.e., when it is a further contact. For example, if the first impact produces a 150 mm crash-box stroke, a second impact shall act on an already 150 mm collapsed crash-box.

This crash-box behavior is simulated in two different ways: with a co-simulation and with a mathematical function. In this analysis, co-simulation means the calculation, by the multibody software, of the crash-box stroke, whose value is sent to the 1d simulation software, which makes use of it to evaluate the force the crash-box is opposing, through its characteristic (Fig. 5). Subsequently, this force value is sent to the multibody software, which calculates the new crash-box stroke. The cycle is repeated every integration step until simulation ends. The mathematical function, instead, avoids the co-simulation by recalling some parameters, appropriately modeled, needed for the stroke calculation and memorize it.

The co-simulation method is very accurate because interfaces with the crash-box characteristic in a direct way, but has a higher computational cost that the mathematical function one.

2.2 Flexible bodies model

Traditional multibody dynamic (MBD) analyses involve the simulation of rigid body systems under the application of forces and/or motions. Analysts try to validate computer simulation results with field test results. In general, the correlation is not exact and there could be a number of reasons for this discrepancy. In the real world, any continuous medium deforms under the application of force. Rigid body simulations do not capture such deformations and this may lead to inaccurate results. Therefore, in order to perform a study which is more relevant to the actual behavior of components, we need to introduce a system of flexible multibody components.

However, flexible bodies introduce an additional set of equations in the system and consequently, have a higher computational cost as compared to rigid body systems. In theory, deformable bodies have infinite degrees of freedom, but mathematical models can be derived by discretization procedures. The finite element method (FEM) is one such procedure. FEM divides

the body into a large number of small elements. The displacements of the connecting nodes of these elements can be approximated as a linear combination of a finite number of mode shape vectors. But, it is not possible to integrate these FE bodies directly into MBD models since the MBD solvers have difficulty solving such large sets of equations. Hence, the concept of flexible bodies was introduced. These bodies have a considerably small number of modal coordinates as compared to the full-fledged FE models. The process of converting an FE model to a flexible body is called Component Mode Synthesis (CMS), a substructuring technique.

The substructuring consists in the subdivision of complete structure in many substructures. The Modal Synthesis allows deriving the complete structures' behavior from its components ones. First, substructures are analyzed independently for their dynamic behavior (natural frequencies and mode shapes) and then, by requiring balance and interface compatibility between substructures, they are assembled to define dynamic behavior of the original structure.

As part of the study of systems with flexible bodies by using multibody codes, the most widely used approach is the Craig-Bampton (CB) method with fixed interfaces. CB method is about the condensation of Finite Elements Mathematical Models, which structural components are discretized with. It allows to redefine large Mathematical Models though a relatively small mass and stiffness matrices and using information on the mode shapes of the components describing the way the structure responds to low frequencies.

The information of the mode shapes consist of all interface modes, expresses in physical coordinate and in a limited set of elastic modes, expressed in modal coordinates. The method was first developed by Craig and Bampton (1968).

2.3 Thrusters model

One of the main issues about the landing maneuver is the impossibility to turn on rockets to restrain the lander descent: in fact, those rockets, to control the lander, should push it in the opposite direction of the descent one, releasing debris towards the ground, contaminating it and derailing the overall mission.

For this reason, this lander descent cannot be controlled, and this could lead to some instability issues and bounces after the impact with the surface, due to the very low gravity on Phobos. Hence, it is needed to turn on thruster the moment the lander impacts with the ground, in order to push it towards the surface: this time, thrusters act to generate a force directed towards the ground releasing debris in the opposite direction, and for the very low gravity they spend much more time to settle down, allowing to take a sample from the uncontaminated surface.

To simulate this behavior, thrusters action is represented by a resultant force applied on the lander barycenter and with a direction towards the ground. Fig. 5 shows the thruster force components:
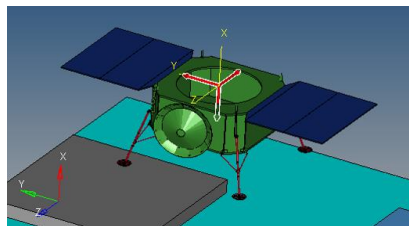

Fig. 5 Thruster force components: The simulated force operates in the direction of negative global X

As shown from the previous figure, the simulation of thrusters has a fixed direction during the overall simulation: this is due to the fact that in this stability analysis, thrusters are considered fixed and are not supposed to change direction during the lander descent. In fact, there is not any control system simulated in this stability analysis. Moreover, the force should start operating the moment the lander impacts the ground, not before: to simulate this behavior, a mathematical function was integrated for the thruster model, which returns 0 as value when there is any contact between legs and the ground and $100N$ (the force supposed to be performed by thrusters) when there is any contact.

In summary, the main inputs described in previous sections are the following:
• The weight of the lander is 1700 kg;
•The initial position of the lander is 2 m from the ground (calculated from the barycenter of the lander to the ground);
•The crash-boxes original length is 300 mm;
•The material of the leg is Aluminium;
•Resultant thruster force is $100N$. It is applied at the barycenter of the lander, in the opposite direction of the global X axis. It activates at the moment the lander impacts with the ground.

3. DOE analysis

Once the lander model is built, it proceeded with the analysis and the choice of the worst case scenario to be analyzed to verify the lander stability. To achieve this result, a DOE (Design of Experiments) was performed: design of experiments is a systematic method to determine the relationship between factors affecting a process and the output of that process. In other words, it is used to find cause-and-effect relationships. This information is needed to manage process inputs in order to optimize the output.

Some key system parameters are changed step by step, in order to find out which of them has a greater influence in other output parameters. The software performs all possible analyses considering the range and the variations of the specific user-defined parameters.

The purpose of this study is to find the worst case scenario where the lander can be found to land. As will be described more carefully below, several parameters, that indicate the roughness and the dangers which the lander may need to lander in, have been gradually varied in the analysis.

As the worst case scenario indication, the angular acceleration of the lander barycenter was chosen: the landing, which would cause the highest barycentric acceleration, was the most critical. Furthermore, because the simulation of the model with crash-box and flexible bodies simulations is costly in terms of time, a simplified model was adopted for the DOE analysis: flexible bodies were removed and crash-boxes too, replaced by fixed joints. These simplifications are sympathetic to the aim of DOE that is the evaluation of the highest angular acceleration. In this preliminary analysis the aim is not to analyze the lander behavior after the impact with the ground, but just to identify the worst scenario, therefore the presence of crash-boxes and flexible bodies, while ensuring greater accuracy of results, would cause a too high computational cost.

The parameters chosen for DOE analysis and their variation range are described in Table 1 (in reference to Fig. 5).

4. Results

In this section are reported the results of DOE analysis and landing stability simulation, using both methods to simulate crash-box behavior.

4.1 DOE analysis results

The worst case scenario which the lander could land in after the DOE analysis was performed, is shown in Fig. 6.

The parameters values after DOE analysis was performed are:
- Initial vertical speed of the lander: -1 $\frac{m}{s}$
- Initial horizontal speed of the lander: 0,2 $\frac{m}{s}$
- Rotational speed of the lander around the Z axis: 5 $\frac{degrees}{s}$
- Lander angular position relative to X axis: 0 degrees
- Lander angular position relative to Z axis: 5 degrees
- Ground slope relative to Z axis: -15 degrees

The angular barycentric maximum acceleration arises on the first impact and his value is 18,4 $\frac{rad}{s^2}$.

Table 1 DOE parameters. Axes are related to the global reference system in Fig. 7

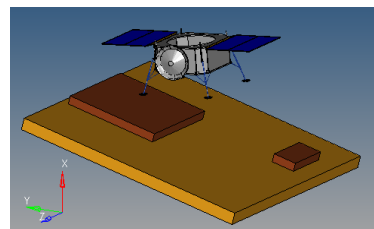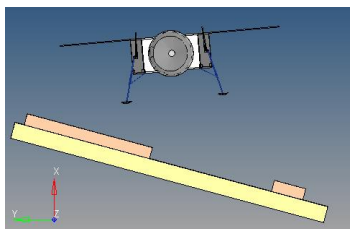|	Minimum value	Initial value	Maximum value	Unit of measurement
Initial vertical speed of the lander	-1	-1	-0,5	$\frac{m}{s}$
Initial horizontal speed of the lander	-0,2	0	0,2	$\frac{m}{s}$
Rotational speed of the lander around the Z axis	-5	0	5	$\frac{degrees}{s}$
Lander angular position relative to the X axis	0	0	45	*degrees*
Lander angular position relative to the Z axis	-5	0	5	*degrees*
Ground slope relative to the Z axis	-15	0	15	*degrees*

Fig. 6 Worst case scenario

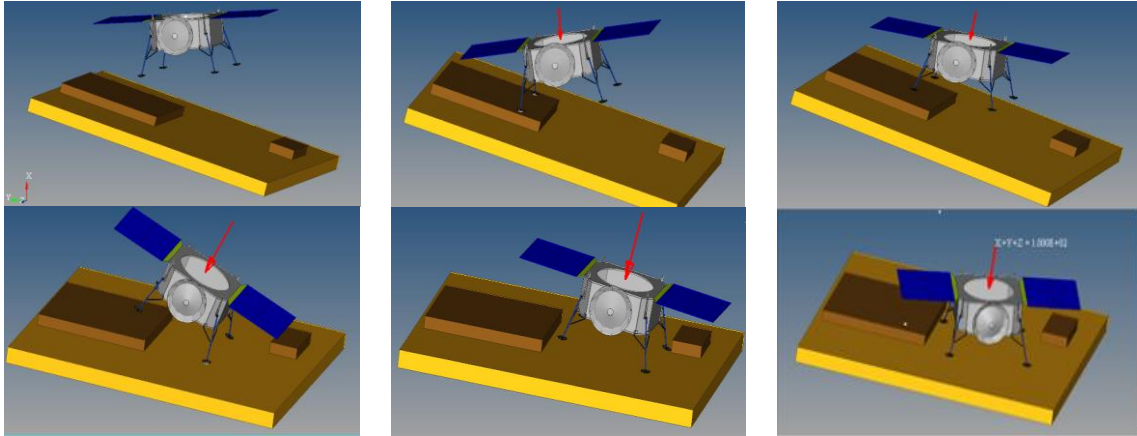## 4.1 Stability analysis: Co-simulation method results

Fig. 7 Lander simulation most important frames with co-simulation for the crash-box behavior. Thrusters' force in red
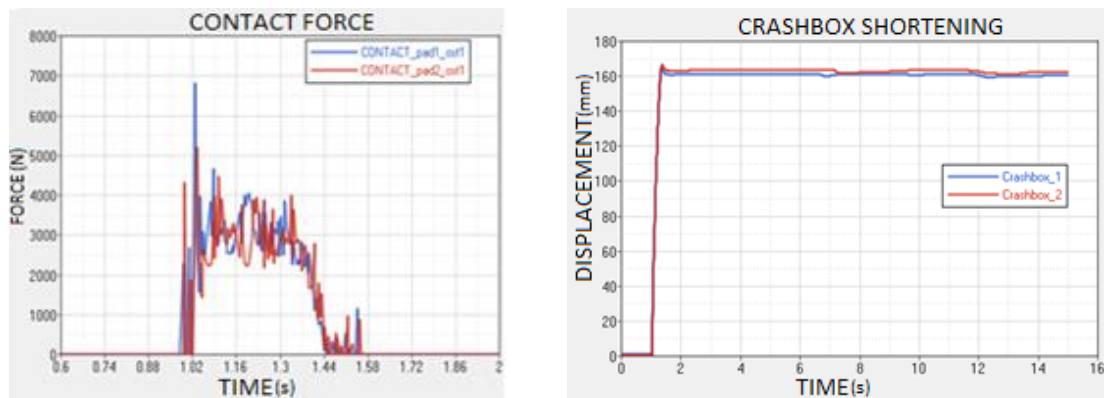

Fig. 8 Contact force and crash-box shortening trends

Fig. 7 shows the most significant frames of landing simulation using co-simulation method for crash-box behavior, using Altair Motionsolve (1985) and solidThinking Activate (1998).

Fig. 8 shows the trend of the contact force and of crash-box' shortening about the legs which collide with the obstacle in the first impact.

The Fig. 8 shows how the contact force does not present a regular pattern, but it is subjected to peaks: this is due to the nature of the simulation, in which the calculation of the force is the result of a co-simulation between two software. This nervousness of the trend of the contact forces had been attenuated by introducing into the multibody model, in correspondence of the crash-boxes, some dampers (with constant c equal to 0.5 $\frac{N*s}{mm}$), with the aim of helping the integration of the solver.

As can be seen from the previous figure, the shortening of the two crash-boxes is 160 mm approximately.

In Fig. 9 is shown the kinetic energy trend.

The biggest jump of kinetic energy trend takes place following the first impact. In this case, in fact, the shortening of the crash-boxes is the greatest, resulting in the greatest absorption of kinetic
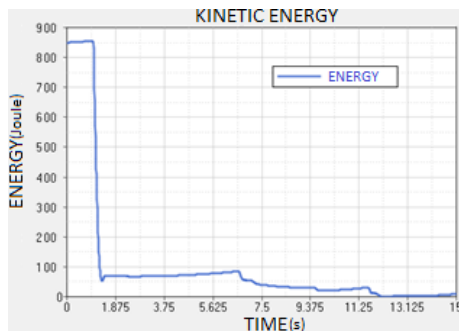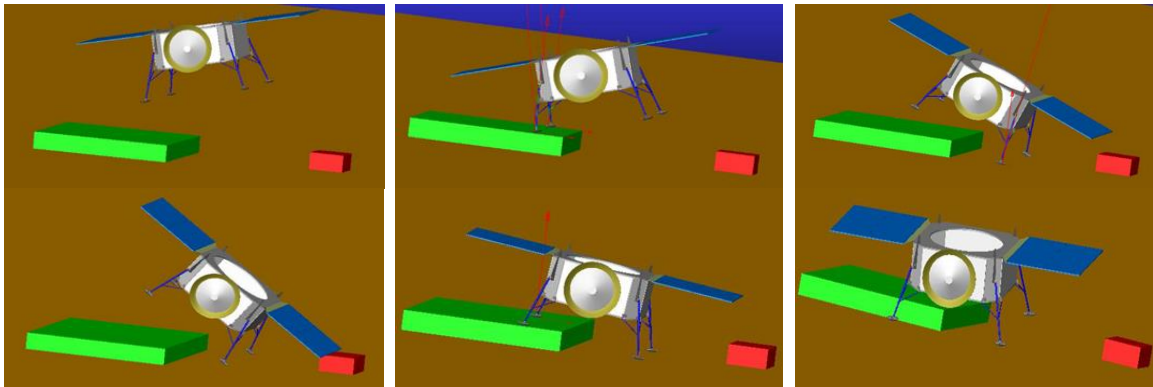
Fig. 9 Kinetic energy trend

Fig. 10 Lander simulation most important frames with a mathematical function for crash-box behavior

energy. This jump is equal to 780 Joule. Calculating the energy absorbed by the two crash-boxes involved in the impact, the result is that the jump that is notable from kinetic energy jump is greater: multiplying the shortening of the two crash-boxes, 162 mm for both, and the force that triggers the collapse 2000 N, the value of about 650 joule is obtained. The differences between the two energy values is for the most part due to the energy of deformation of the flexible bodies integrated in the model, but also to the damping present in the formulation of contact between the lander and the ground and the fictitious damping introduced in the legs of the lander to allow to the solver greater stability.

Finally, an important finding relates to the time when the thrusters must be activated: they are turned on at the time of the first impact (after 1 second of simulation) and must remain active until the stability of the lander (after 23 seconds of simulation), so the result is 22 seconds. This data could be useful for possible future developments, as it establishes how much fuel would be necessary to bring in the spacecraft.

4.2 Stability analysis: mathematical function method results

Like with the co-simulation method, with the mathematical function, the lander stability is achieved too, thanks to the activation of thrusters, after the first impact with the obstacle. Fig. 10 shows some frames of the simulation with this method, using MSC Adams (1963).

It can be noted from the previous figures the action of the thrusters: they are able to bring the
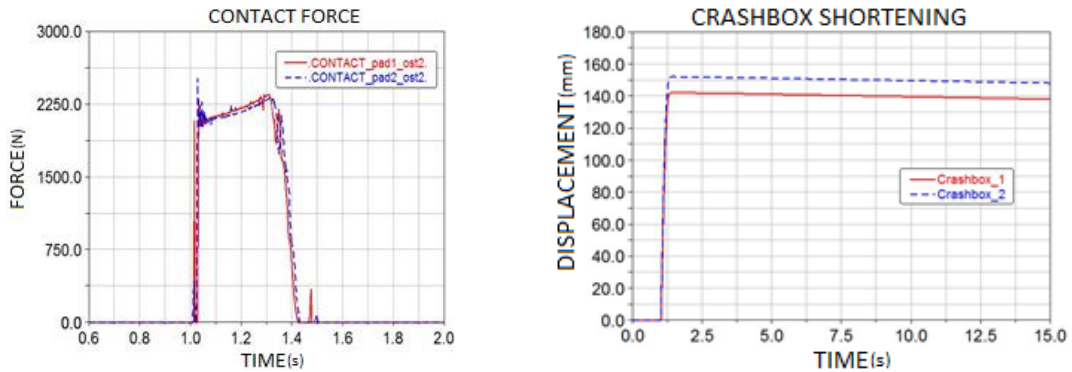
Fig. 11 Contact force and crash-box shortening trends

lander from an unstable configuration (fourth frame) in a stable configuration (sixth frame), pushing it towards the surface. Following figure shows the trends of the contact forces and consequent crash-boxes shortening on the first impact.

As shown in Fig. 11, the contact forces have a more regular trend and do not exhibit peaks that instead characterize trend of the co-simulation method ones. This is due to the difference of the simulation, which does not require the help of another software.

Moreover, the shortening of the crash-boxes reaches lower values compared to the previous analysis, reaching values of 153 mm and 142 mm, with a difference of about 12% from the co-simulation method ones, such as to be able to say that the results obtained are comparable.

The lower values of crash-box shortening in this case from the co-simulation method ones are justified looking at the contact forces trends, in Figs. 8 and 11: in fact, with the mathematical function method, the contact force has a lower value (2,25 kN from Fig. 11) from the results of the co-simulation method (mean value of around 3kN from Fig. 8). This difference can be explained by the usage of two different softwares: both have a different way to simulate contacts between bodies, which reflects in contact forces results.

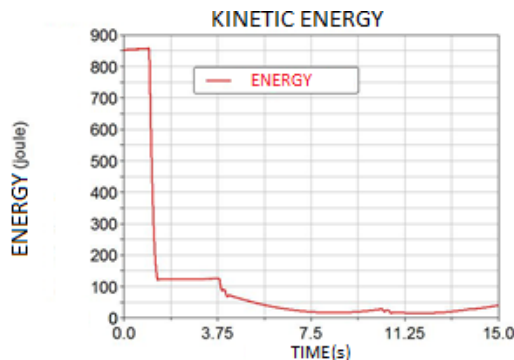In Fig. 12, lander kinetic energy trend is shown:

Fig. 12 Shortening value of the crash-boxes on the first impact

The greatest absorption of kinetic energy by the lander is on the first impact, in which the

kinetic energy decreases by 750 joule. Even in this case, the kinetic energy absorption is not entirely covered by the work done by the two crash-boxes which collapse, but the remaining portion has to be attributed to the energy of deformation of the flexible bodies and the internal damping of the contact formulation.

In general, even with a different formulation of crash-box behavior, the lander stability is achieved, with the help of thrusters which push the lander on the Phobos surface from the first impact.

5. Conclusions

The question behind this work is if it is really necessary to perform analyses using specialist software to study the landing phase on a celestial body. At the end of this paper, we can say that is crucial to increase the so high-risk phase reliability, trying to foresee and prevent any situation which could put at risk the final result, baffling the work of years and the total investment.

There are several reasons for such a high risk, and they are mainly linked to the celestial body low gravity and the local nature of surface, that is often merely conjectured. These risk elements can concur to cause dangerous bounces and, in the worst case, the overturning: simulation work with reliable mathematical models plays a very important role to prove the project's robustness, thanks to the possibility to consider simultaneously present more unfavorable elements during the overall landing phase and to lead the tuning of an adequate landing system, based on the impact absorption of the legs, using crash-box element, and the lander stabilization, using thrusters.

This paper, then, regards the stability analysis of a landing gear and studies in deep the dynamic and the stabilization after the impact with the surface, providing a concrete help to the activities in progress at Thales Alenia Space on this theme. After have built a lander model, a DOE analysis has been performed on it, in order to identify the worst case scenario, which the landing module could have to land in. Some parameter, considered significant to identify a certain scenario for the landing, have been chosen. The indication to evaluate the case criticality for the stabilization is the barycentric angular acceleration. These are the worst values: $15°$ for the ground inclination, to simulate the landing on a stretch of a slope, a lander vertical velocity of $1 \frac{m}{s}$, horizontal velocity of $0.2 \frac{m}{s}$, an angular velocity of $5 \frac{degrees}{s}$ and an angular position of $5 \, degrees$, in the opposite direction of the ground slope.

On this scenario, stability analysis was performed, using two different multibody software. The reason of this is because, in order to execute a near-to-reality analysis, the crash-box was simulated in two ways: by a co-simulation with a 1-D simulation software, which calculates the value of the crash-box compression force, based on the value of the crash-box stroke calculated by the other software, and with a mathematical function modeled and parametrized properly, which does not require a co-simulation with other programs, saving computational time.

Using the DOE analysis model, some features were added in it: crash-box simulation, as mentioned before, and flexible bodies instead of rigid bodies for lander legs, in order to perform a more accurate simulation. Furthermore, to ensure the lander stability and to remedy to the very low gravitational pull, the ignition of thrusters was conjectured: they start working the moment the lander impact the Phobos surface and produce a force, simulated like applied at the lander barycenter. Analyses results show how, with both crash-box behavior simulation methods, the lander stability is obtained on the ground. Finally, the results obtained by these two methods are differed by a 12% approximately, and then we can conclude that the cross check between the two

software and from the simulation approach performed, can be considered reliable.

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