Mars landing operation (Rocket Atlas V)

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Abstract

A dynamic system model of the landing operation of the rocket *Atlas V* on Mars is described and implemented in the modeling language *Modelica*. The governing equations of a mathematical model describe how the values of the unknown variables (i.e., the dependent variables) change when one or more of the known (i.e., independent) variables vary. The rocket thrust force allowing a successful landing on the surface of Mars is determined. On the other hand, different physical properties of the rocket, such as, its velocity, acceleration, mass, and altitude, are carefully investigated.

Keywords: Modelica, MarsLanding, Rocket *Atlas-V*.

1. Introduction

Landing of a rocket on a planet is a relatively delicate operation. Several parameters come into account, including the gravitational force applied by the planet on solid bodies (like the rocket) located within its gravitational field, the thrust force applied by the rocket engine, the velocity and the altitude of the rocket over its movement.

During the landing operation, the rocket must overcome gravity through its engine's thrust, i.e. the law of action-reaction. According to IssacNewton, every action corresponds to an equal and opposite reaction. In this context, the force produced by the rocket's engine acts directly on its trajectory during landing. With low strenght, the engine might cause a crash-landing on the planet's surface. On the other hand, powerful engine force will cause the deflection of the rocket, which in this case would not reach the surface. Therefore, it's necessary to establish a good balance between the different forces governing the rocket.

The aim of this study is to model the landing of the rocket on the surface of Mars. Several control parameters will be defined and their values will be adapted to achieve a good landing.

2. Problem description

The present investigation consists of a rocket named *Atlas V* of mass M_R, located at a distance h from the surface of Mars and moving vertically with an initial velocity V_0. The rocket's engine applies a thrust force F_R. We will assume that the core of Mars is an inertial frame of reference and we will not account for the effects of the Sun's gravity. Mars is assumed to be spherical, homogeneous, of mass M_M and radius R_M. The rocket undergoes an external force F_M applied by the planet under the effect of the gravitational field g_M. Fig. 1 represents an illustrative scheme of the problem.

Table 1 shows the different control parameters characterized the rocket and Mars.

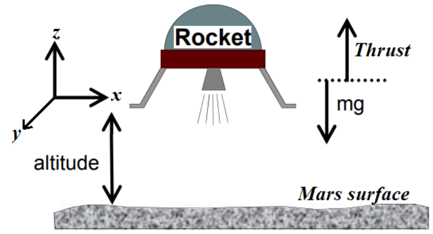

Figure 1: Illustrative scheme of the problem

Table 1: Control parameters using in governing equations

	Parameter	Symbol	Value	Unity
Rocket	Initial mass	M_R	1038.358	kg
	Initial velocity	V_R	2003	$m.s^{-1}$
	Initial altitude	h	59404	m
	Mass loss factor	MLF	0.000277	-
Mars*	Mass	M_M	$0.64171.10^{24}$	kg
	Radius	R_M	$3.3962.10^{6}$	m
	Surface gravity	g_M	3.71	$m.s^{-2}$
Constants	Universal gravitational constant	G	$6.672.10^{-11}$	$m^3.kg^{-1}.s^{-2}$

(*):https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html

At an altitude h from the surface of Mars, the gravity applied to the rocket is defined by the following equation:

$$g_r = \frac{G \times M_M}{(R_M + h)^2} \tag{1}$$

The rocket velocity is constant at the initial instant $t = 0$, it undergoes a temporal variation when the rocket moves down on the surface, so it is evaluated through the following equation:

$$V(z) = \frac{dh}{dt} \tag{2}$$

The rocket acceleration is defined as follows:

$$\ddot{a}(z) = \frac{dV(z)}{dt} \tag{3}$$

The rocket mass variation with respect to the altitude is described as follows:

$$\frac{dM_R(z)}{dt} = -MLF \times |F_R| \tag{4}$$

3. Results and discussion

Figure 2 illustrates the temporal variation of the rocket altitude over the landing operation. From this figure, it appears that two phases characterize the altitude variation. First, the landing operation stars at the altitude $h = 59404\,m$ at $t = 0$, a very quick decrease in the altitude is observed until $t = 43.2\,s$, while the second phase is sustained over the entire range $43.2 < t \leq 120$, the rocket shutdown progressively and slowly, compared to the first

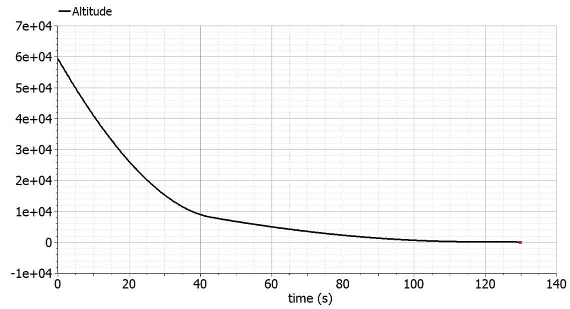

Figure 2: Temporal variation of the Rocket altitude

phase until touchdown with the Mars surface at zero altitude.

Figure 3 shows the gravity variation when the rocket approaches the Mars surface calculated from Eq. 1. It is clear that a high increase in gravity is observed in the first phase, because in this phase a quick decrease of the altitude h occurs. On the other hand, the gravity gradually approached the Mars gravity $g_M = 3.71$ at the end of the second phase.

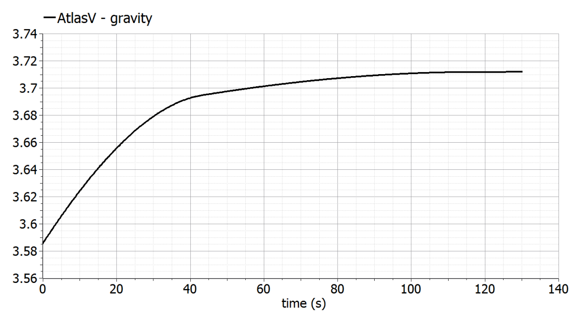

Figure 3: Temporal variation of the gravity

Lets us consider the variation of the rocket's velocity and acceleration. The rocket initially has a high negative velocity and a quick decreased velocity behaviors is observed in the first phase, as illustrated in Fig. 4, which is justified by the high acceleration gradient. However, in the second phase to achieve a safe landing, the velocity decrease slowly (low acceleration) until touchdown the surface at $t = 120s$

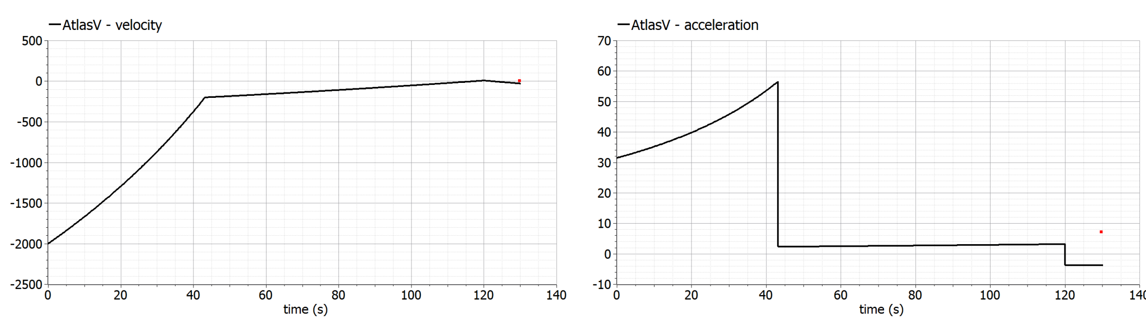

Figure 4: Temporal variation of the rocket velocity and acceleration

The rocket's mass is related to fuel consumption, which is the amount of fuel used by the rocket's engine per unit distance. Over the first phase, when the rocket's motion is characterized by high velocity, the fuel consumption is quickly increased. Herein, the Rocket's mass is significantly reduced, as illustrated in Fig. 5. However, the relative small velocity in the second phase implies a moderate fuel consumption. This means that the mass decreases slowly, compared to the first phase. The mass variation remains constant when the rocket reaches the surface at $t = 120s$.

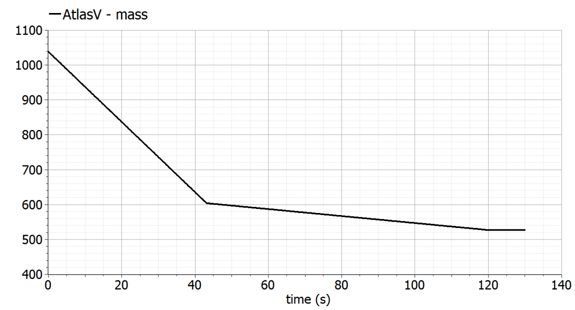

Figure 5: Temporal variation of the Rocket mass

Until now the study showed the variation of the altitude behavior using a constant thrust force in the first phase. It should be noted that safe loading depends on the initial thrust force. Now, let's plot the altitude variation for various thrust forces. Figure 6 illustrates the altitude behavior for three typical force values $F_1 = 46000\,N$, $F_2 = 36350\,N$ and $F_3 = 36000\,N$. To set this up, we create a new model block with properties referencing the main Mars-landing block. Each property will provide its own set of values to plot. The numerical results plotted in Fig. 6 show that the force F_2 allows a safe landing on the Mars surface, while the low initial thrust force F_3 will cause a crash at below-zero altitude. In the opposite situation, the use of the high initial force F_1 will involve the rocket pass thousands of kilometers from the planet (minimum altitude $h = 19166.9\,m$), due to the fact that a too much thrust is applied.

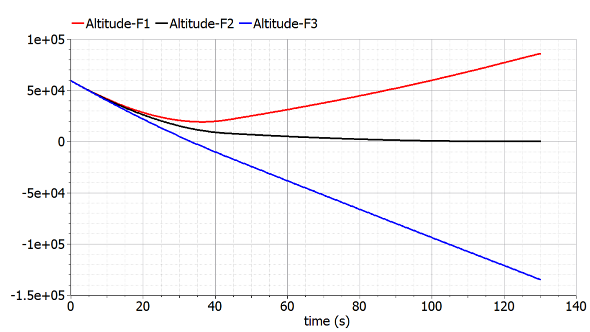

Figure 6: Effect of thrust force on the altitude variation

4. Conclusion

In this study, the Mars landing operation is modeled and simulated using the *Modelica* software. This example shows how small changes in the thrust force can have a critical impact on the success of the mission. A pair of the thrust forces is determined, i.e. 36350 N in the first phase and 3616.16 N in the second one.

Multi-way connections of static pipes

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Abstract

In this study, the design of the fluid connectors is explained. A model demonstrates the use of distributed four static pipes connected to two Boundary source. Validation of the present model is carried out.

Keywords: Fluid flow, Pipes, Validation.

1. Problem description

The example in this study consists of the thermo-hydraulic-type model corresponding to equipment in which only hydraulic phenomena type is involved. The model includes four static pipes. The first pipe is connected directly with a Boundary source component. The three others are connected in parallel. The respective outputs of these three pipes are connected to a second Boundary component. Notice that the prescribed static pressure on the left Boundary 1 is higher than on the right one. Still, the fluid flows from left to right. A liquid water is considered as a fluid in this model, as illustrated in Fig. 1.

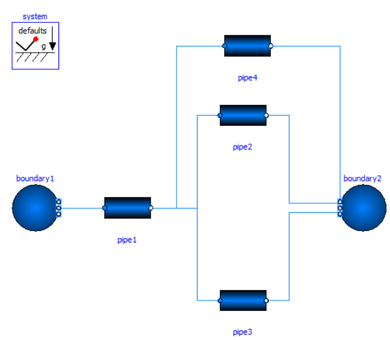

Figure 1: Modelica scheme of the model

2. Results and discussion

Table 1 illustrates some constants that is considered in the present model.

Table 1: Constants parameters considered in the model

Constant	Symbol	Value	Unity
Gravitational acceleration	g	9.81	$N.kg^{-1}$
Temperature of water	T	20	$^{\circ}C$
Density of water	ρ	995.586	$Kg.m^{-3}$
Kinematic viscosity of water	ν	1.005×10^{-6}	$m^2.s^{-1}$
Specific enthalpy	h	83680	$J.kg^{-1}$

Lets now defined the geometrical and hydraulic parameters related to the boundary and static pipes, see table 2.

Table 2: Constants parameters considered in the model

Pipe	Diameter $D\,[m]$	Length $L\,[m]$	Mass flow $q_m\,[Kg.s^{-1}]$	Velocity $V\,[m.s^{-1}]$
1	1	20	24919	31.8685
2	1	20	4683.34	5.9895
3	1.5	20	13446	7.6426
4	1.25	30	6789.66	5.5572
Boundary	Number of ports	Temperature $T\,[°C]$	Pressure $P\,[bar]$	
1	1	20	2	
2	3	20	-	

In order to verified the accuracy of our results using Modelica, analytical values are calculated in order to carry out a comparison with the numerical values, namely, the pressure at the outer port of the pipes. In this context, some hypothesis are considered: the fluid (i.e., water) is incompressible and inviscid, the total mechanical energy of the fully developed flow regime in the pipes.

- Bernoulli's equation between inner and outer ports of the each pipe:

$$\frac{P_{int}}{\rho\, g} + \frac{V_{int}^2}{2g} + z_{int} = \frac{P_{out}}{\rho\, g} + \frac{V_{out}^2}{2g} + z_{out} + h_{fl} \tag{1}$$

  where P is the pressure, V the water velocity, z the vertical coordinate system and h_{fl} the linear pressure drop.

  Taking into account the flow conservation and fully developed flow regime the velocity at the inner and outer ports are equals $V_{int} = V_{out}$, for the circular horizontal pipe $z_{int} = z_{out}$, the pressure at the outer connect port is as follows:

$$P_{out} = P_{int} - \rho\, g\, h_{fl} \tag{2}$$

- Lets us determine the linear pressure drop $h_{fl} = f \frac{L}{D} \frac{V^2}{2\,g}$, with f is the fraction factor estimated thought the calculation of the Reynolds number $Re = \frac{V \times D}{\nu}$, the relative roughness $= \frac{\varepsilon}{D}$ and using the Moody diagram.

The obtained results with Modelica and the analytical value of the pressure at the outer port of each pipe are illustrated in table 2. It appears that Reynolds number order of magnitude is greater than 10^6, which is clearly that the turbulent flow occurs within the four pipes. Furthermore, an excellent agreement between the P_{out} calculated analytically and using the Modelica software is obtained, with a maximal relative deviation of less than 1%, provided the model is accurate.

Table 3: Numerical and analytical results

Pipe	$Re \times 10^7$	$\frac{\varepsilon}{D} \times 10^{-5}$	f	$\Delta P = \rho\, g\, h_{fl}$	P_{int}	$P_{out}(analy)$	$P_{out}(Modelica)$	Error (%)
1	3.1602	2.5	0.0095	0.9573	2	1.0427	1.0363	0.61
2	0.5939	2.5	0.01	0.0356	1.0427	1.0071	1	0.70
3	1.1368	1.67	0.0098	0.0379	1.0427	1.0049	1	0.48
4	0.6888	2	0.0099	0.0364	1.0427	1.0063	1	0.62

3. Conclusion

In the present simulation, the validity of a model consisting of four pipes is investigated. The validation test shows the performance of our model.