LAUNCH VEHICLE DESIGN AND GNC SIZING WITH ASTOS

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ABSTRACT

The European Space Agency is currently involved in several activities related to launch vehicle designs (FLPP, Ariane 6, VEGA evolutions, etc). Within these activities ESA has identified the importance of developing a simulation infrastructure capable of supporting the multi-disciplinary design and preliminary GNC design of different launch vehicle configurations.

Astos Solutions has developed the Multi-Disciplinary Optimization (MDO) and Launcher GNC Simulation and Sizing Tool (LGSST) under ESA contract. The functionality is integrated in the ASTOS [1] software and is intended to be used from early design phases up to Phase B1 activities. ASTOS shall enable the user to perform detailed vehicle design tasks and assessment of GNC systems, covering all aspects of rapid configuration and scenario management, sizing of stages, trajectory dependent estimation of structural masses, rigid and flexible body dynamics, navigation, guidance and control, worst case analysis, launch safety analysis, performance analysis and reporting.

1. INTRODUCTION

This paper will present how the workflow for the vehicle optimization and design of launcher GNC algorithms is realized in ASTOS®, DCAP [2], ODIN [3] and Matlab/Simulink®.

The first step comprises the definition and design of the launch vehicle including the structural mass estimation on substructure level as function of the dimensioning load case. The reference solution is used for the GNC design in Matlab/Simulink® and first performance analysis tasks with rigid body dynamics.

In a second step ODIN is used for the finite-element model export, which again can be used as input to the mode-shape export computed by DCAP. Alternatively a free-free-beam model can be utilized in combination with spring damper elements between stages and at engine suspensions. The mode shapes are used for linearization of the ASTOS flexible dynamics and for controller design in Matlab.

In a third step Matlab/Simulink® is used for the controller design implementing body-bending filters to account for the flexible dynamics and propellant sloshing. PID and low-order state-space controller are used for the thrust vector control and a non-linear state-space feedback for the actuator control.

Finally, the impact of the launch safety analysis on the launch vehicle design is discussed.

2. SOFTWARE TOOLS

2.1 ASTOS

ASTOS (Analysis, Simulation and Trajectory Optimization Software) is a simulation and optimization environment to simulate and optimize trajectories for a variety of complex, multi-phase optimal control problems. In the last twenty years it has been successfully applied in several industrial or ESA projects in the field of launcher, re-entry and exploration missions. Just to provide some examples the following projects can be mentioned: Ariane 6, Ariane5, Vega, Next European Launch System, Automatic Transfer Vehicle, Hopper, Skylon, Fly-back Booster, etc.
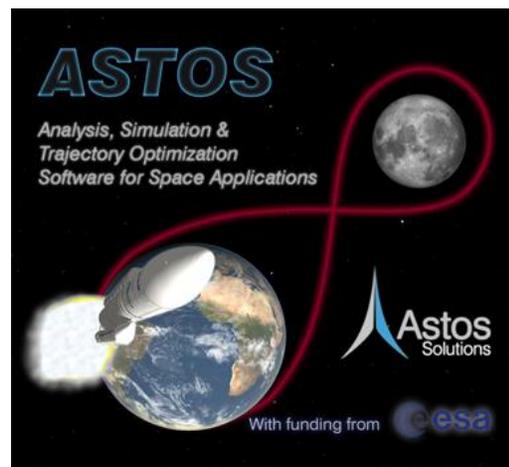

Figure 1. Splash screen of ASTOS 8.

ASTOS consists of fast and powerful optimization programs, CAMTOS, SOS, etc. that handle large and highly discretized problems, a user interface with multiple-plot capability and an integrated graphical iteration monitor to review the optimization process and plot the state and

control histories at intermediate steps during the optimization.

ASTOS comprises an extensive model library [4], which allows for launcher and re-entry trajectory simulation and optimization without programming work.

ASTOS provides a Simulink s-function, which allows it to act as environment and dynamics block inside a GNC environment under Simulink. Moreover ASTOS allows the physical definition of the launcher model and the design of several sub-systems in a single optimization run.

ASTOS includes the interface to the structural analysis tool ODIN as well to the multi-body flexible dynamics tool DCAP.

ASTOS provides several safety analyses to evaluate the human risk associated to re-entering fragments; it can compute the casualty and fatality index associated to a destructive re-entry or to a launcher failure. The fragments are propagated considering atmosphere interaction: drag and demise. A model for automatic explosion and fragmentation is provided.

2.2 DCAP

DCAP (Dynamics and Control Analysis Package) is a suite of fast, effective computer programs that provides the user with capability to model, simulate and analyze the dynamics and control performances of coupled rigid and flexible (NASTRAN interfaced) structural systems subjected to possibly time varying structural characteristics and space environment loads.

It uses the formulation for the dynamics of multi-rigid/flexible-body systems based on Order(n). This avoids the explicit computation of a system mass matrix and its inversion, and it results in a minimum-dimension formulation exhibiting close to Order(n) behavior, n being the number of system degrees of freedom. A dedicated symbolic manipulation pre-processor is further used in the coding optimization.

2.3 ODIN

MT Aerospace has developed the Optimal Design INvestigations (ODIN) tool as an answer to improve the structural mass estimation. It allows a rapid evaluation of a broad range of tank and structural components.

The ODIN tool incorporates a wide library of analytical formulas to size the elementary structures, such as domes, cylinders or struts. For each elementary structure various design options can be investigated, from basic thin-walled isotropic, to orthogrid, sandwich and other. The design options are evaluated for numerous design criteria including strength, global buckling, and local buckling modes.

Within the MDO project, Astos Solutions has designed a user-friendly GUI for ODIN, see Figure 2.
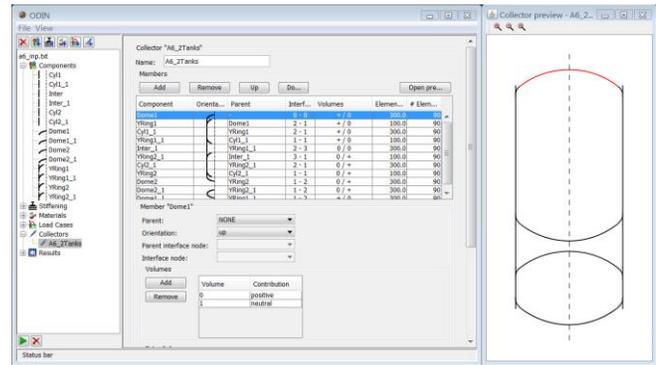

Figure 2. Example of ODIN GUI

ODIN is coupled to an external solver to optimize the dimensions of each stiffening design options. The optimization takes into account all failure criteria (strength, general and local buckling) as well as manufacturing limits and factors. For example for an orthogrid stiffened cylinder, ODIN can calculate the mass optimal dimensions of pocket width, wall thicknesses, rib height etc.; while ensuring positive margins of safety for strength, general and local buckling. The optimization can be carried out for several load cases simultaneously.

2.4 Matlab/Simulink

Matlab (matrix laboratory) is a numerical computing environment. Under the utilization of its tool Simulink, that has the capability of modelling, simulating and analyzing multi-domain dynamic systems, the guidance navigation and control analysis is performed. Via a S-Function the extensive ASTOS model library is linked to the Simulink model. This allows the application of the ASTOS environmental and flight dynamics database.

3. VEHICLE DESIGN

The process of designing a vehicle via a step-wise approach is the most effective in the field of space launchers. The rationale is the progressive knowledge that the designer achieve during the process itself: starting with high-level requirements, then moving toward a preliminary design until the detailed design of each sub-system.

In order to follow this procedure, ASTOS presents several levels of design models in the most important fields: aerodynamics, mass budget and propulsion. This step-wise approach is not only driven by the missing knowledge of some details in the early phases of the design, but also by the performance of the optimization software. The duration of the process is affected by the complexity of the models involved; therefore in the early phases it is more efficient to use fast models and analyze several potential concepts. Once the most promising concept has been identified, detailed models could be applied to refine the design of the vehicle.

The MDO modules of ASTOS have been funded by two consecutive ESA studies ranging from 2008 till 2014.

A part from the technical achievements reached during these projects, one additional positive aspect is that ASTOS has been effectively used for the design of launchers by Astos Solutions, agencies and commercial companies worldwide. This procedure has been efficiently applied in several projects; just to mention the most recent ones, Ariane 6 (e.g. ESA NELS) and a new small Japanese launcher.

Figure 3. Next generation launcher (courtesy of ESA)

3.1 Optimization procedure

In NELS, the different configurations proposed have been analyzed in a systematic way using simple design models (i.e. linear correlation between the propellant mass and the structural mass). Once this fast assessment has been completed, the MDO modules of ASTOS have been applied to the "winning" concepts in order to reduce the level of inaccuracy of the solution.

The inclusion of ODIN within the optimization process is not applicable due to the computational time required, therefore a similar tool, ODINMER, is employed in order to prepare interpolation tables for each material, shape and stiffening concept. The independent variables for these tables are the load-cases (i.e. fluxes and pressures) as well as the dimensions of the elements. During the optimization ASTOS is accessing these tables to identify the required structural masses until an optimal is found.

The procedure within ASTOS is a loop of several steps, this is required by the time required to compute some aspects (e.g. load-case):
1. creation of the vehicle model including aerodynamics,
2. generation of an initial guess without any load-case,
3. computation of load-cases,
4. optimization of trajectory and design parameter,
5. repeat point 3. and 4. until convergence is reached.

The convergence is achieved when the result of the optimization with the new load-case is not differing from the result with the old load-case. The converged result is then validated with ODIN for the structural analysis and RPA [5] for the propulsion analysis.

Figure 4 provides a screen-shot of the vehicle representation inside ASTOS. An upper stage with enclosed tanks is shown in a "under the fairing" configuration. The blue and yellow arrows are over-imposed to identify the forces that are considered during the computation of the load-case analysis. The horizontal black dotted lines identify the stations where the load-cases are computed; the propellant within a tank (grey cylinders) is modelled as a series of slices.
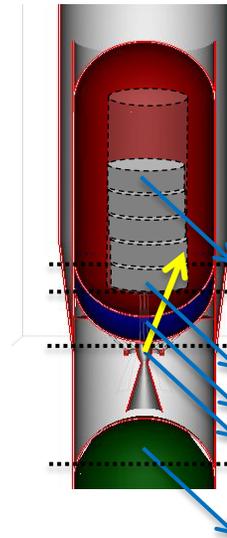

Figure 4. Detail design stage in ASTOS.

3.2 Results

Figure 5 provides an example of load-cases as computed and visualized by ASTOS. The abscissa represents the main axis of the vehicle; the blue and black curves are respectively the buckling and strength fluxes; the green curve is the bending moment. The vehicle is similar to Ariane 5 with side boosters: that explains why at one X value, there are two or more curves with the same color: one refers to the main core and one to the side booster.
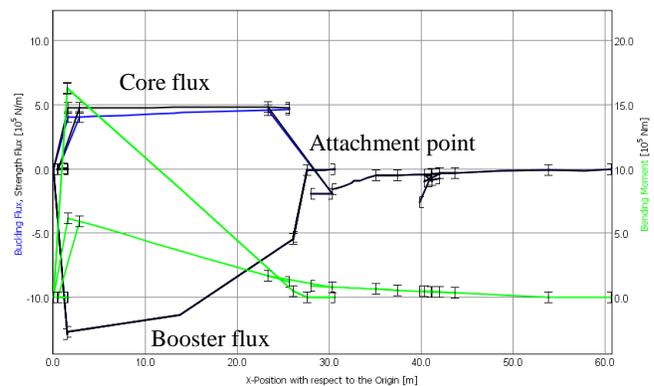

Figure 5. Example of load-case (MDO).

Figure 6 presents an example of the ASTOS automatic reporting feature with the sub-elements of the Stage 1. For

each entity the mass is provided together with the stiffening, dimensions and load-cases. This table includes values optimized directly by ASTOS (e.g. height), values interpolated from MER tables (mass), input parameters (stiffening) and values computed by the analysis (e.g. strength flux).

Stage 1 Components	Mass [kg]	Stiffening	Height [m]	Diameter [m]	Strength Flux	Strength pres	Buck Flux
Aft_Bulkhead_Fuel_Tank	451.2	sandwich	2.4	4.7	0	2.23	1
Aft_Bulkhead_Oxidizer_Tank	302.8	orthogrid	2.4	4.7	-195	3.37	-17
Aft_Skirt_Cylinder	74.6	isotropic	1.2	4.7	0.2	0	0
Cylindrical_Part_Fuel_Tank	**2,667.2**	**sandwich**	**20.4**	**4.7**	**333**	**2.15**	**1.4**
Cylindrical_Part_Oxidizer_Tank	469.1	orthogrid	4.8	4.7	-155	2.89	-66
Forward_Bulkhead_Fuel_Tank	450.8	sandwich	2.4	4.7	2.4	0	2.4
Forward_Bulkhead_Oxidizer_Tank	295.8	orthogrid	2.4	4.7	-29	0	-15
Forward_Skirt_Cylinder	467.4	isotropic	2.4	4.7	-118	0	-118
Interstage_Cone	876.3	isotropic	3.7	4.7	-112	0	-112
Intertank_Cylinder	634.6	orthogrid	7.1	4.7	425	0	-197

Figure 6. Structural mass table (MDO).

4. GNC DESIGN AND ANALYSIS

The design of the GNC sub-system is an important aspect for a launcher; during its trajectory several maneuvers are performed and a robust and reliable GNC is the key for a successful launcher. ESA acknowledged the importance of this aspect via the LGSST project.

The decision to place this topic after the vehicle design chapter is due to the typical process within a project: the design (or definition) of the launcher is a prerequisite for the GNC design and analysis (see Figure 7). ASTOS is used for these tasks, whereas the definition of the GNC and the simulations are performed in Matlab/Simulink with ASTOS as S-Function responsible of providing the dynamics.
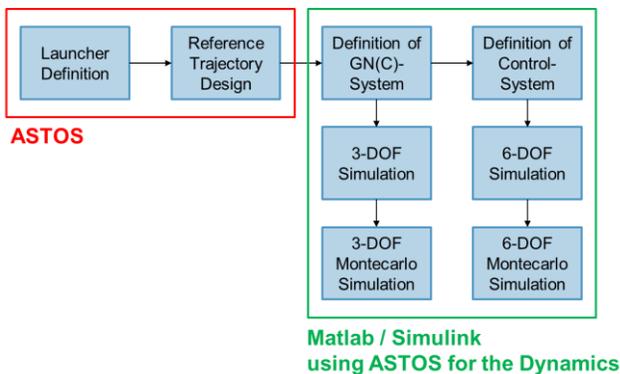

Figure 7. GNC design procedure.

4.1 Reference trajectory

Within ASTOS the definition of the vehicle and the creation of the reference trajectory can be performed in a single step. Once the design process has converged (see section 3.1) the resulting trajectory can be used as reference one. The practice differs slightly from the theory; minor modifications are introduced in the ASTOS scenario in order to improve the robustness and performance for the GNC simulations. These are typically in the field of aerodynamics and atmosphere where fixed tables are used instead of potentially changeable models.

4.2 3-DoF simulation

Once the reference trajectory is available the real GNC work can start. It is good practice to evaluate first the guidance and navigation part in a simple 3-DoF model. The attitude of the vehicle is an output generated by Simulink with no correlation with the controllability of the vehicle.

The preparation required for this step is minimal on ASTOS side: the attitude for all the phases is set in a way that it can be accessible to Simulink.

The definition of the GNC models inside Simulink is not presented in this paper; the interested reader could request additional information from the authors.

During the 3-DoF simulation, open- and closed-loop guidance can be used depending on the trajectory phase: typically the open-loop guidance is applied during the atmospheric part of the trajectory. There the attitude is interpolated from the nominal one as function of time or altitude or speed or a combination of those. The resulting trajectory differs from the nominal one due to differences in the environment model and errors in the navigation module.

As soon as the dynamic pressure reduces below critical values (lower than 1kPa); the attitude can be fully optimized and closed loop guidance can be applied. In this part of the simulation the target final orbit can be used to reshape the attitude profiles. This is required in order to compensate for the differences accumulated during the atmospheric part of the trajectory.

Figure 8 provides a comparison between the reference attitude profiles and the closed-loop guidance; respective as red and blue curves. Both yaw and pitch are presented in degree as function of the flight time in seconds.

This is a clear example of the reshaping performed during close-loop guidance: in the last phase the guided attitude differs from the reference one.
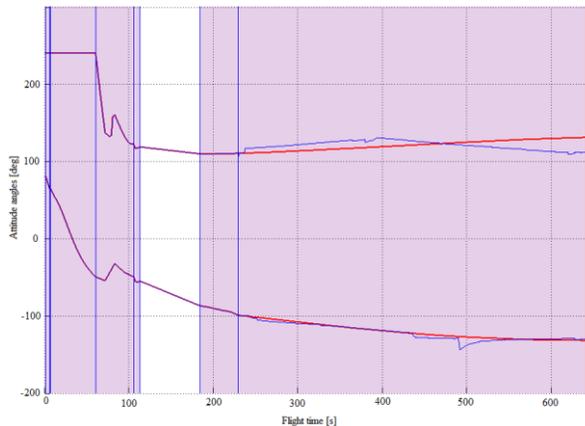
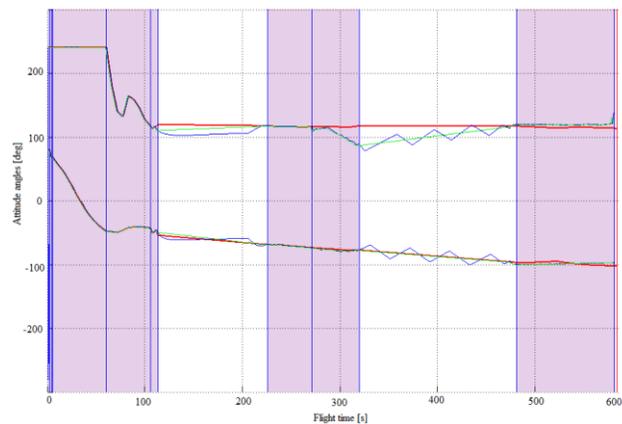**Figure 8. Reference attitude (red) vs. guidance (blue)**

Figure 9. Reference (red), guidance (green) and controlled attitude (blue).

4.3 6-DoF simulation

Once the guidance and navigation provide good performance, the control part can be defined and applied in a 6-DoF simulation.

The changes in the ASTOS scenario are again quite reduced.

- The attitude becomes a state, an entity that is integrated as function of the right-hand side.
- The aerodynamics is augmented with the moment coefficients.
- The orientation of the main engines with TVC (thrust vector control) is set to be visible from Simulink.
- The attitude thrusters are set as active and their status are set to be visible to Simulink.

The scenario is then ready to be used in a 6-DoF simulation with the control algorithms defined within Simulink.

The control algorithm should select which channels (attitude thrusters and/or TVC) to use in order to achieve the attitude defined by the guidance. This simulation is the most precise representation that can be achieved at this level of the project.

Figure 9 provide an example of the attitude as result of the control within Simulink compared to the reference attitude; respective as blue and red curves in degrees. The abscissa is the flight time in seconds. The white areas where the differences are higher are coast arcs: in order to minimize the use of propellant of the attitude thrusters, a high error is accepted there. The differences in the pink areas instead are generated by the reshaping performed in the close-loop guidance.

The 6-DoF simulations are used for both the rigid body and the flexible body dynamics. For the latter some modifications are required in ASTOS and Simulink, but the workflow is identical. Details are presented in chapter 5.

4.4 Monte Carlo analysis

The last steps in the GNC analysis are performed as Monte Carlo simulations in both 3-DoF and 6-DoF.

The vehicle flies under several uncertainties and random errors; these are typically present in the environment, in the vehicle mass and inertias, in the actuators and in the sensors.

The most efficient way to evaluate the effect of these disturbances on the GNC design is to insert them in an automatic batch process as random or uniform distributions. ASTOS is well equipped also for this step (see Figure 10); the "Batch-Mode Inspector" allows the user to create a set of actions that can involve nested loops. The most typical list includes:

- perturbation of disturbances,
- Simulink simulation,
- evaluation of variables (e.g. final orbit),
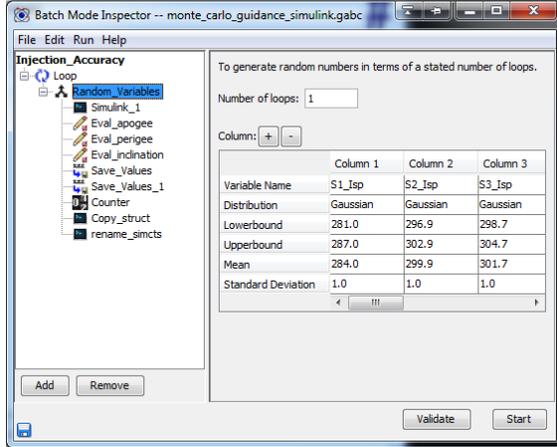- save of variables.

Figure 10. Example of Monte Carlo analysis within ASTOS.

The Batch mode inspector is also performing some automatic post-process analysis: computation of average, one-sigma and distribution of each variable saved. These additional outputs allow a fast analysis of the robustness of the GNC design and well as the sensitivity of some disturbances on the overall design.

Figure 11 provides an example of this post-process analysis: the residual propellant for the attitude thrusters at the end of the mission. The distribution is quite uniform in the range between 12 and 15 kg. The conclusion could be that the allocated propellant is sufficient for this mission.
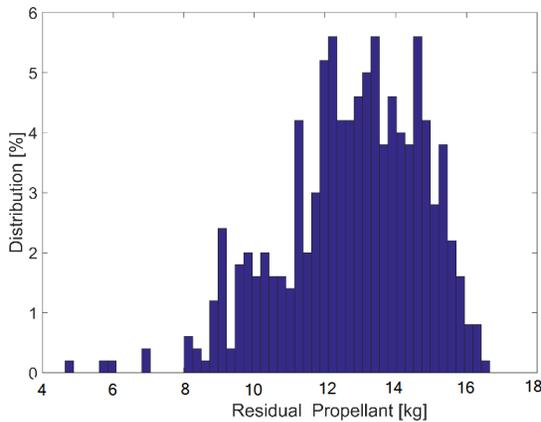

Figure 11. Distribution of residual propellant for attitude thrusters.

A complete different distribution is presented in Figure 12; there the final orbit inclination is presented. Most of the results are very near to the average value of 47 degree with few results spread between 46 degree and 48 degree.

It could be concluded that the GNC is very robust in respect to the final orbit inclination.
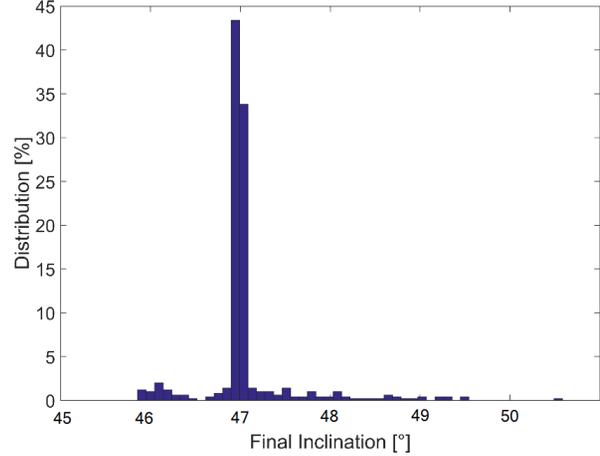

Figure 12. Distribution of final inclination.

5.   FLEXIBLE DYNAMICS

Two main aspects are considered while analyzing the vehicle: the liquid propellant sloshing inside a tank and the model of the vehicle as a flexible body.

The analysis of the flexible dynamics is an important aspect while analyzing the GNC of the vehicle. The flexibility of the vehicle increases the input error in the navigation part and the output error of the control part because the position of the sensors and the attitude of the thrusters are changing due to the flexibility of the body. Moreover the modelling of the vehicle as a flexible body allows the computations of the natural frequencies of the vehicle; frequencies that the controller should avoid to reduce resonance oscillations.

5.1 Propellant sloshing

Sloshing dynamics is modelled for a cylindrical tank by masses attached to the container with linear spring damper devices at the Y and Z rotation axis (X is the main axis of the tank).

The sloshing mass can be defined as:
- constant value or percentage of initial propellant e.g. propellant reserve,
- percentage of current propellant (variable mass),
- percentage or mass profile as function of time (variable mass).

The sloshing propellant is modelled as slice on top of the non-sloshing propellant and defines the center of mass accordingly.

Figure 13 is a model for sloshing using linear springs and dampers for a cylindrical tank with diameter d filled up to the height h. In static condition the masses are on axis and the springs exert no force.

It is composed of one static mass with two parameters, a mass m_0 and the inertia I_0. For each sloshing mode to be

modeled, an additional mass is defined which is fastened to the tank center by a spring-damper device. The neutral position of the springs is also located at the center of the tank. The number of sloshing modes is defined by n. Each one has a mass m_n, height h_n, measured from the center of mass of the static liquid, a spring constant k_n and a damping constant c_n.

To model sloshing in two dimensions, two orthogonal springs are attached to the same mass instead of only one. In the vertical direction of the tank (X) no sloshing occurs.

Most of the equations required are taken from [6] chapter "2 Mathematical Model". For the damping parameters the equations are from [7] section "2.2 Viscous Damping for Tanks of Various Shapes" for circular cylindrical tanks.
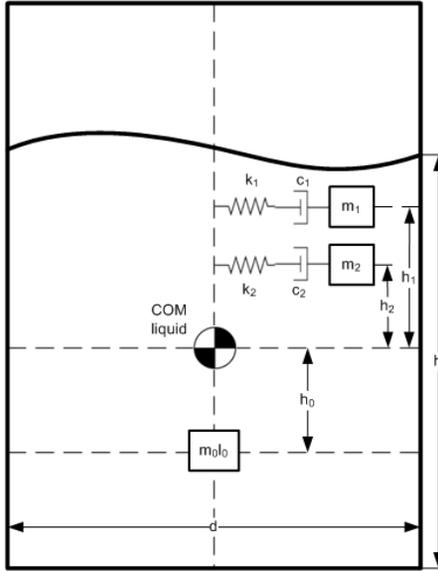

Figure 13. Sloshing model [8].

5.2 Flexible body

The vehicle itself is approximated with beams. Both flexible aspects represent the flexible model which is linearized at certain Points of Interest (POIs). Typically such POIs are generated before and after a stage separation or at the point of maximum dynamic pressure.

After the linearization the flexible launcher is represented by a second order system. The used equations are based on [8]. Figure 14 depicts the used quantities.

The global system of equations of motion, considering both rigid and flexible degrees of freedom, is defined as follows:

$$\begin{bmatrix} \dot{x}_r \\ \dot{x}_f \end{bmatrix} = \begin{bmatrix} A_r & 0 \\ 0 & A_f \end{bmatrix} \begin{bmatrix} x_r \\ x_f \end{bmatrix} + \begin{bmatrix} B_r \\ B_f \end{bmatrix}$$

where the subscripts r and f identify rigid and flexible quantities respectively.

The flexible part of the state space model for n_{modes} is defined as:

$$[\dot{x}_f] = \begin{bmatrix} \dot{q}_i \\ \ddot{q}_i \end{bmatrix} = A_f \begin{bmatrix} q_i \\ \dot{q}_i \end{bmatrix} + B_f$$

$$A_f = \begin{pmatrix} a_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & a_{n_{modes}} \end{pmatrix}$$

$$a_i = \begin{pmatrix} 0 & 1 \\ -\omega_i^2 & -2 \cdot \omega_i \cdot \zeta_i \end{pmatrix},$$

$$B_f = (0 \quad Q_1 \quad 0 \quad Q_2 \quad \dots \quad 0 \quad Q_{n_{modes}})^T$$

The rigid part A_r keeps unchanged from the rigid model. The changes on B_r due to the flexibility can be found in [8].

The generalized forces Q are computed as a combination of thrust and aerodynamic forces for each mode. Thrust forces are defined using the deflection angle, the rotational acceleration and the distance between the pivot point of the engine or nozzle and the center of mass of the rotating engine part. Also thrust moments are considered.

Aerodynamic normal forces are derived from the distributed aerodynamic coefficients CNA_j and CNB_j acting at the local center of pressure COP_j with local angle of attack and side slip angles α_{loc} and β_{loc}.

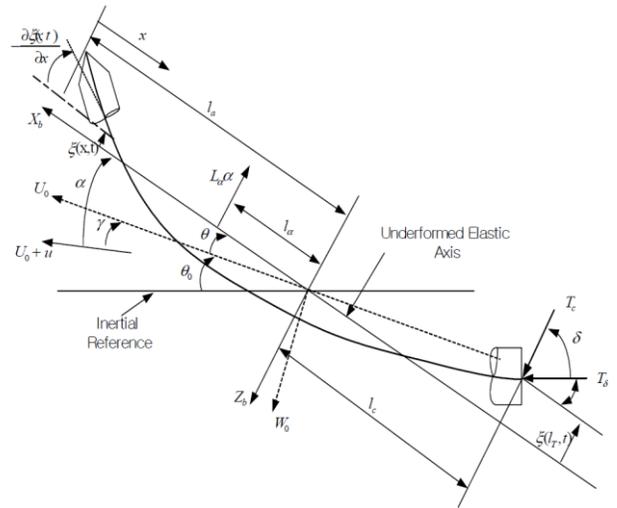**Figure 14. Elastic deformation of a beam [8].**

The rigid body dynamics (B_r) are affected by the flexible body dynamics considering:

- elastic deflection angles and displacement at the position of the thruster pivot point
- elastic displacement of the center of mass of the sloshing fuel at each time point effecting the vehicle inertia
- total normal aerodynamics force as sum of each local contribution.

5.3 Results

The presented data refer to computations performed at Astos Solutions and should be considered as an example of the software capability.

The trajectory is separated in some events, e.g. ignition of stage 1, max dynamic pressure, etc. At each event the natural frequencies of each stage is computed.

For simulation purposes only frequencies below 10Hz are used. This is necessary because in the example presented the integrator of the simulator runs with 100Hz and the separation of at least one order of magnitude is required to avoid instabilities.

The propellant sloshing is providing low frequencies, in the order of 1Hz and below.

The integration of ASTOS and DCAP provides also the mode shapes of the vehicle at the trajectory events. This provides a graphical representation of the displacement and of the rotation of the flexible body.

As shown in Figure 15 the mode shapes include the effect of the propellant sloshing (at 30 m of the main vehicle axis).
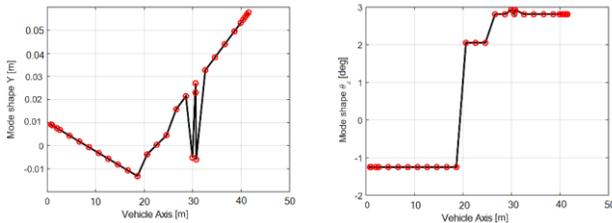

Figure 15. Mode-shape example.

Once the natural frequencies are computed, the controller has to be updated in order to avoid instabilities (typically at the end of the burn phases). In particular oscillations around 2-3 Hz are observed in the original controller. A band-stop filter can be applied and the result is presented in Figure 16 for the angle error: the red line is the original controller error, the blue line the filtered one.
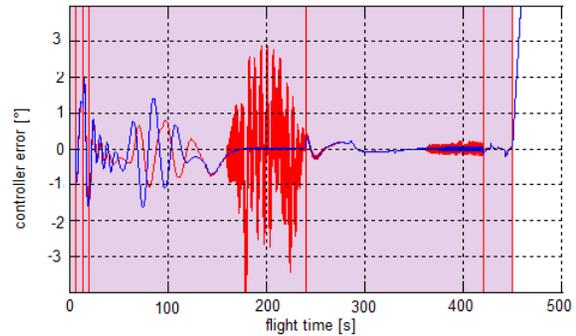

Figure 16. Unfiltered control error (red) vs. filtered (blue).

6. SAFETY ASPECTS

ASTOS has been used for the assessment of the human risk in several projects: e.g. re-entry of ATV 1, staging of third stage of VEGA, distribution of impact point of SHEFEX 2.

Recently new modules dedicated to the safety aspects of launchers have been added. These have an effect on the design of the vehicle and on the GNC sub-system.

6.1 Launch Safety

This analysis allows estimating the risk of casualty and fatality for a vehicle when performing a launch from its launch pad; the analysis is based on the ascent trajectory of the reference design. The analysis is using the automatic explosion model based on stochastic methods available in ASTOS DARS [9]. It combines the results of the debris impact points with the risk analysis module to compute the risk of casualty and fatality in case of failure during the ascent trajectory. This is achieved using the population density of the areas crossed by the impact point line.

The explosion model is applied to each time step of the trajectory with the filter acting on the perigee altitude: if the perigee of the vehicle is higher than 85 kilometer, no explosion is performed and no risk is computed. The rationale is that for higher perigee altitudes, the fragments may not re-enter or demise during the high energetic re-entry.

The position and dry mass of the launcher are used as input for the explosion model. Each fragment is propagated until it demises or impacts.

Another important aspect to be considered is the seed number used to generate fragments due to the explosion. ASTOS includes three different options:

- Fixed seed will produce always the same distribution of fragments along the whole trajectory.
- Incremental seed will guarantee different explosions along the trajectory, but based on the same sequence of seed numbers. Therefore, the results will be reproducible.

- Random seed will generate always different seed numbers. In this way two consecutive runs of the same test case will lead to different results, because different fragments will be generated at the same time step.

Figure 17 shows the casualty probabilities as function of the flight time: the time when the explosion is performed. An incremental seed is used. The probability is shown as logarithmic scale to appreciate the peaks that occur around 150 and 530 seconds: there the fragments are re-entering in areas near small populated land. The last peak is for fragments reentering on a large populated land (i.e. a continent).
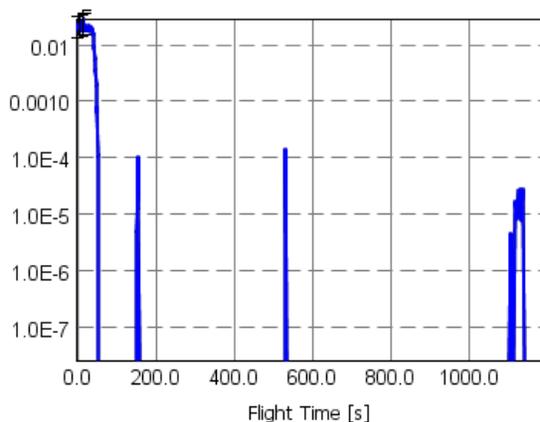

Figure 17. Casualty probability from launch safety.

Additionally ASTOS computes the FAA flight corridor as defined by US regulations [10]. Depending on the dimension of the vehicle some classes are defined and the extension of the corridor is dependent on this classification.

6.2 Re-entry safety
This analysis is present in ASTOS since many years, but in the latest version of the software automatic explosion and fragmentations models have been added to DARS.

This analysis is not only propagating all the fragments considering the defined material characteristics, but also the complete trajectory of them is saved and can be plotted within ASTOS (Figure 18).
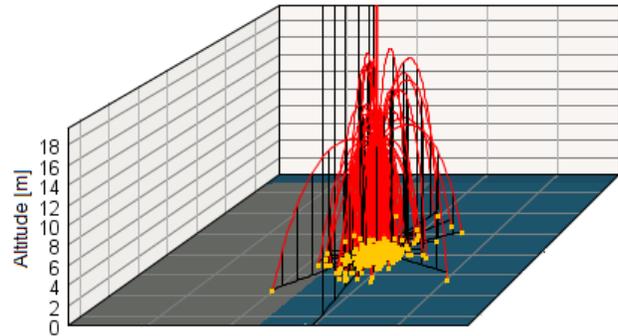

Figure 18. Explosion at launch-pad.

Each fragment will produce a risk associated to the human population density, to the air-traffic density and to the ship-traffic density.

6.3 Shock wave model
This safety analysis is performed with an approach similar to the one presented in section 6.1. The position of the vehicle is analyzed at each time step of the trajectory; there an automatic explosion is performed and the resulting blast wave is computed.

Since in the literature there is not a clear agreement on the best formulation, several shock wave models have been implemented in ASTOS [2] in order to compute the blast area: the minimum distance from the center of the explosion where the static overpressure produced by the blast of the explosion is below a certain value.

All shock wave models use equivalent TNT mass as input values to compute the blast area. This is multiplied by the propellant mass at each time step and by a correction factor smaller than 1. This is required because a part of the explosion energy goes into the fragmentation and acceleration of fragments. This correction factor is compatible with the data gathered during the observation campaign of ATV 1 Jules Verne.

The user can specify an overpressure and ASTOS computes the respective intersection between the blast area and the planet surface: within that perimeter the overpressure is higher than the value specified. Since for most of the launchers, the first seconds of the trajectory the flight is vertical, the area computed is very similar to a circle. Afterwards the altitude of the vehicle becomes too high and there is no intersection between the blast area and the planet surface.

7. CONCLUSION
The implementation of new modules in ASTOS has improved the capability of the software to answer the need of aerospace engineers during the preliminary design of the vehicle.

The funding of ESA through multi-year projects made possible a comprehensive implementation in the most important areas of the vehicle design: structure, propulsion and aerodynamics. The inclusion of interfaces to Matlab/Simulink, ODIN, DCAP and RPA added the missing analysis capability. Advanced safety analyses are present in the software.

ASTOS is therefore an efficient simulation infrastructure to design launchers up to the phase B1.

This software is commercially available not only to ESA, but to all interested entities worldwide.

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