LAUMBS: A NEW SOFTWARE FOR LAUNCH VEHICLE DESIGN AND VERIFICATION DURING ASCENT AND PAYLOAD INJECTION

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ABSTRACT

The design of a launcher is a complicated process involving multiple disciplines. On top of this the disciplines are not independent but are interconnected through a series of design variables that have opposite effects in the disciplinary performance.
LauMBS (Launcher Multibody Simulator) is a software for multi-disciplinary launcher design focused on the mechanical aspects and providing a link to the GNC design.
The software framework, based on two existing tools (DCAP and ASTOS), provides the building blocks to simulate a complete launcher scenario considering vehicle flexibility, sloshing effects, stages separation, engine pressure oscillations and complex aerodynamic loads distribution.

1. LAUNCH VEHICLE CHALLENGES

Numerical simulation has become an essential activity for the development and design of launch vehicles, due to the complexity of such systems. The simulation of the flight dynamics is nowadays of particular interest. Such kind of analyses have the purpose to investigate the behaviour of the vehicle in flight subjected to environmental interactions.
The software designed to perform flight dynamics analysis should be able to predict the way the vehicle moves in space depending on the forces and moments acting on it. This task is achieved using an adequate dynamic model for the vehicle and suitable techniques to predict the loads acting on it.
Few applications are available on the market which can perform such kind of analysis [1][2][3], but none of them can consider every aspect involved in this complex dynamic scenario.

Even if most of the available software consider the launcher as rigid, a launch vehicle is basically a long slender beam [4], thus it is structurally very flexible. One critical risk for a flexible flying vehicle ascent flight control system is the interaction between the ascent flight control and the elastic launcher structure [5]. If the first bending mode frequencies are close to the frequency regime of the control system, the entire vehicle dynamics could get unstable.

The lateral dynamic force resulting from the lateral motion of liquids in the propellant tanks is known as the propellant sloshing. There is a strong coupling between the sloshing effect, the mechanical structure and the control system. If the sloshing frequencies are close to the control system frequency, resonance might cause vehicle flight instability.
In order to address this contribution, high fidelity sloshing analyses are performed via Computational Fluid Dynamics (CFD) simulations. This kind of investigations are very accurate, nevertheless they require significant computational effort and specialized knowledge. The sloshing dynamics can also be represented by equivalent mechanical systems such as either pendulum mass model or spring mass model [6][7].

Launcher stages separation is one of the most significant technical and system engineering challenges [7]. The process can be divided into two phases. First the actual disconnection of the two components takes place. This task is accomplished by explosive bolts or clamps, pneumatic latches or explosive shaped charges.
The second phase instead, involves the forces which actually take the components apart and generate the relative motion. This is accomplished by retrorockets, pneumatic thruster or elastic spring elements.

Solid propulsion is the simplest type of chemical propulsion in rocket science.
The operative condition of a Solid Rocket Motor (SRM) with particular propellant grain geometry is characterized by low amplitude but sustained pressure and thrust oscillations. The oscillations level does not seem to be threatening for motor life, but it reduces the rocket motor performance and could damage the payload if coupled to the structural modes and thus to launcher structure and payload [8][9].
In order to investigate the coupling between aeroacoustics and structural dynamics of a SRM usually it is necessary to solve the coupling between a CFD analysis and a Finite Elements Method (FEM) simulation. Because of the huge computational burden involved, these kinds of investigations are very slow and expensive. However, analytical solution is not viable way to perform such kind of analysis.

During the launcher ascent, the airflow over the vehicle produces shear force due to skin friction between air particles and vehicle body. The pressure distribution and its variation around the vehicle surface generate a net force acting on the vehicle and a net moment about its centre of gravity [7]. Moreover, if the vehicle is flexible enough, interactions between aerodynamic, elastic and inertial forces occur [10].

The objective of the LauMBS tool is to perform mechanical design and simulation of the launcher vehicle reproducing all the previous mentioned complex phenomena.

2. DCAP AND ASTOS PACKAGES

In order to obtain a reliable tool, LauMBS is based on two existing software: DCAP and ASTOS.
DCAP (Dynamic and Control Analysis Package) is a no-frills, rational, fast multibody software tool [11], designed for assessing space systems and devices.
The main DCAP features are:

- a symbolic multibody formulation;
- variable-mass rigid and flexible bodies;
- space environments;
- sloshing modelling;
- portable interface for Simulink and NASTRAN;
- graphical user interface approach.

With more than 30 years of heritage, DCAP is considered by the European space community as an alternative, independently-coded simulations tool with consistent I/O files, for highly reliable cross-validations.
ASTOS (Analysis, Simulation and Trajectory Optimization Software for Space Applications) is a multi-purpose tool for space applications [12], which has been originally designed for trajectory optimization, provides now modules for a variety of analysis, simulation and design capabilities for the whole project life-cycle. The built-in plotting and animation tools as well as its brought range of supported scenarios and applications bring ASTOS towards unique all-in-one software. The key feature of ASTOS are:

- a built-in trajectory and multi-disciplinary design optimization;
- a wide range of mission, performance and system analysis;
- built-in plotting and animation tools;
- Simulink and dSPACE interfaces for closed-loop simulations, HIL and SCOE applications;
- built-in batch-processing engine and configuration tool;
- interfaces with SQL database and Excel.

3. HOW LAUMBS WORKS

LauMBS combines the features of DCAP and ASTOS into a common framework.
The LGSST ESA project [12] attempted merging those tools together but only via a static link. DCAP was used merely as pre-processor of the flexible component properties. During the simulation process, only ASTOS was actually running. LauMBS aimed to overcome this limitation and to let DCAP be part of the numerical simulation.

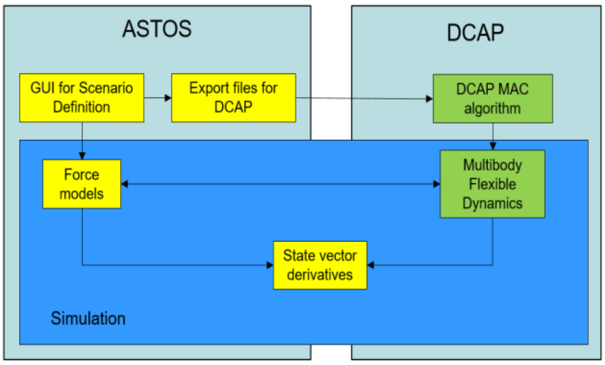

Figure 1. Interactions of DCAP and ASTOS in LauMBS software

ASTOS is the master software and it is the only tool the user interacts with. The vehicle model and the launcher scenario are set up through the ASTOS GUI, see Fig. 1. Once the simulation is triggered by the user, ASTOS exports all the required DCAP files for the definition of the multibody system according to the model. DCAP then computes the vehicle flexible properties (if needed), such as mode shapes and frequencies. Finally the numerical simulation starts and, for each integration step, the following actions are performed:

- ASTOS provides to DCAP the external forces such as aerodynamic loads, gravity accelerations and actuator output;
- DCAP computes the system dynamics and evaluates the state derivatives;
- ASTOS performs the numerical integration of the state derivatives.

The final results can then be analysed in the ASTOS post-processing view.

4. MULTIBODY LAUNCHER STRUCTURE

The launcher mechanical structure is defined by the user at the scenario initial conditions. Before the simulation takes place, ASTOS generates the required DCAP files with the mechanical properties of each component for different propellant filling levels.

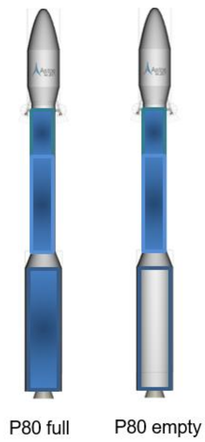

Figure 2. VEGA launcher P80 engine tank full on the left (100% filling level) and empty on the right (0%

filling level)

Fig. 2 show the VEGA launcher first stage with full and empty propellant tank.
A total of 11 configurations, from 0% to 100%, of propellant filling level, are computed by LauMBS during the initialization. Tab. 1 reports the mechanical properties of the VEGA first stage function of the tank filling level.

Table 1. Mechanical properties of a launcher stage for different configurations (from filling level 0 to 1)

Var	Mass	Ix	Iy	Iz	Ixy	Ixz	Iyz
0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0
0.1	61.6	4.921532	227.2901092	227.2901092	0.0	0.0	0.0
0.2	123.2	9.325008	454.3211904	454.3211904	0.0	0.0	0.0
0.3	184.8	13.210428	681.0932436	681.0932436	0.0	0.0	0.0
0.4	246.4	16.577792	907.6062688	907.6062688	0.0	0.0	0.0
0.5	308.0	19.4271	1133.860266	1133.860266	0.0	0.0	0.0
0.6	369.6	21.758352	1359.8552352	1359.8552352	0.0	0.0	0.0
0.7	431.2	23.571548	1585.5911764	1585.5911764	0.0	0.0	0.0
0.8	492.8	24.866688	1811.0680896	1811.0680896	0.0	0.0	0.0
0.9	554.4	25.643772	2036.2859748	2036.2859748	0.0	0.0	0.0
1.0	616.0	25.9028	2261.244832	2261.244832	0.0	0.0	0.0

During the ascent flight simulation, DCAP makes use of the current propellant filling level to interpolate between the two closest configurations and retrieve the current component mechanical properties.

4.1. Flexible properties and MAC algorithm

Each vehicle component can be modelled as rigid or as flexible. DCAP has available a linear Euler-Bernoulli flexible beam model which can be used in LauMBS without the need of any other external FEM tool.
The beam model allows to approximate the flexibility and the frequency content of the real launcher structure. When flexible components are present, the interpolation of the mechanical properties is not straightforward as for rigid bodies.

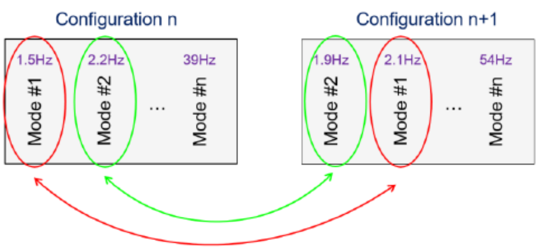

Figure 3. Mode shapes interpolation between different configurations

For each flexible component, DCAP computes the mode shapes and the frequencies for every configuration. However, the same mode shape might be in different array location for different configurations.
For example the mode shape in the first array location, in a certain configuration *n*, might switch to the second array location in the next configuration *n+1*, as shown in Fig. 3. Therefore, the interpolation routine might end up interpolating different mode shapes only because they are in the same array position among adjacent configurations.

In case of flexible components, a dedicated MAC algorithm (Modal Assurance Criterion) is executed before the simulation takes place, in order to correctly sort the mode shape vectors for each configuration.
The MAC algorithm indeed automatically identifies the most similar mode shapes between two set of data.

5. SLOSHING DYNAMCS

A spring-mass system is adopted in LauMBS as equivalent mechanical model to simulate the sloshing effect of the tank propellant.

The mechanical slosh model is composed of two parts:

- one static body with mass and inertia parameters;
- additional masses (for each sloshing mode) fastened to the tank centre by a linear spring-damper device.

The neutral spring position is located at the centre of the tank. Each sloshing mass is defined by:

- a mass;
- a height, measured from the centre of mass of the static liquid;
- a spring stiffness;
- a damping value.

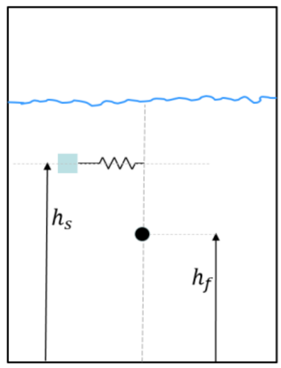

Figure 4. Sloshing model for a cylindrical tank

Two different sloshing models are implemented in LauMBS for cylindrical and spherical tanks and are mainly applicable for accelerated flight, such as launcher scenarios. Fig. 4 and Fig. 5 show the fixed and sloshing masses for the cylindrical and the spherical models.

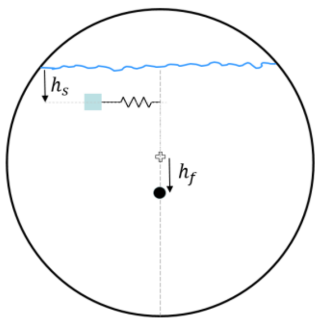

Figure 5. Sloshing model for a spherical tank

The user is required to provide only three high level inputs:

- tank shape: either cylindrical or spherical;
- number of sloshing masses;
- propellant kinematic viscosity.

Two spring-dampers are attached to each sloshing mass, in perpendicular directions, in order to simulate a three dimensional sloshing dynamics. Therefore each sloshing mass corresponds to two sloshing frequencies.
LauMBS computes internally all the required settings for the mechanical model such as mass, inertia, stiffness and damping values.

The sloshing dynamics of a launcher tank propellant has been verified against an analytical handmade model simulated in Matlab using different numerical integrators. The launcher tank has been excited with a sinusoidal lateral force in order to activate the sloshing phenomenon. The results, as shown in Fig. 6, have proved the correct implementation of the mathematical models.

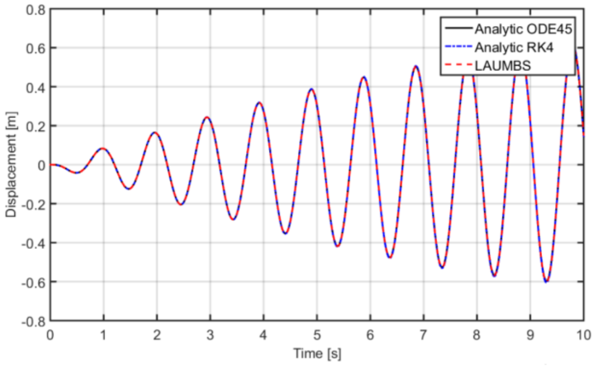

Figure 6. . Sloshing mass offset displacement for an external force acting on the tank with a frequency of 1 Hz

6. SEPARATION DEVICES

The separation process between stages or payloads is accomplished in LauMBS by using the jettison logics. The user defines in the ASTOS GUI when a certain stage has to be jettisoned. This action enables a DCAP feature, called transition, which actually separates the bodies.
However, this process only affects the configuration of the mechanical system but it does not embed any separation force or torque.

In order to reproduce a more realistic components separation, LauMBS allows to add separation devices.
Three types of separation devices are available:

- thrust force;
- hard-stop device;
- clamp band.

The first two devices are general purpose actuators available in ASTOS which can be used to obtain the required behaviour.

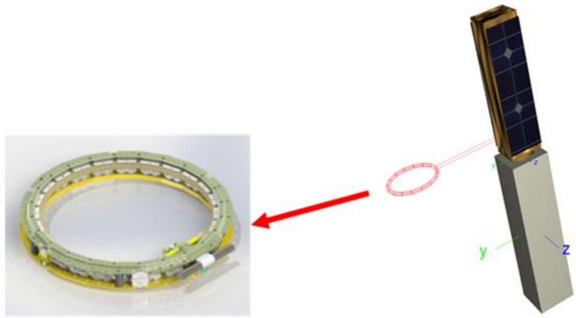

Figure 7. Clamp band device between the upper stage and the payload

The clamp band devices, see Fig. 7, have been specifically developed for payload separation. The user is only required to specify the diameter, the number of springs and their elastic properties (either individually or in batch). An equally distributed spring-damper devices are placed along a circumference reproducing the mechanical system of typical commercial clamp bands.

7. ENGINE PRESSURE OSCILLATIONS

The ignition and the complex fluid-dynamics of solid propellant stages cause pressure oscillations. This phenomenon is the effect of complex feedback mechanism involving vortex shedding and acoustic resonant mode. The few experimental data available [9] show a typical oscillation frequency around 50-60 Hz.

There is no equivalent mechanical model, available in literature, which is able to simulate the disturbances of the propulsion system. The best way to consider those effects in a multibody environment, is to provide the disturbance loads directly as an input of the system.
In LauMBS the user can provide two types of input:

- force profile (time domain;)
- coloured noise (frequency domain).

The former type is straightforward. The force profile due to the pressure oscillations is summed up to the main thrust generated by the engine.
In the latter case, the frequency content of the propulsion disturbances is associated by the user to a coloured noise. Typically, a red noise signal well represents the solid engine propulsion oscillations as shown in Fig. 8. The spectrum is converted into a time domain signal directly during the numerical simulation and it is then added to the main engine thrust.
The average engine thrust will be thus affected by the pressure oscillations disturbances during the flight.

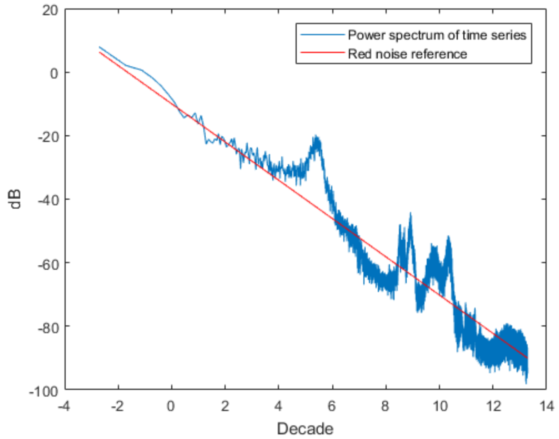

Figure 8. Red noise signal representing the pressure oscillation behaviour

8. AERODYNAMIC LOADS

The aerodynamics during the launcher ascent flight is a very complex environment and aero-elastic phenomenon might also occur if there is interaction between the vehicle flexibility and the inertial forces.
The aerodynamic loads computation in LauMBS consists of several iterations between ASTOS and DCAP. The position, velocity and attitude of each component is provided by DCAP. ASTOS computes the aerodynamic loads in terms of forces and torques depending on the aerodynamic coefficients defined by the user. Finally ASTOS injects the aerodynamic loads into the DCAP multibody system.

Two different aerodynamic models are available depending on the input data and the desired accuracy.

8.1. Non distributed aerodynamics

Non-distributed aerodynamics means that the aerodynamic force and moment of the overall vehicle are applied only on one node of the structure.
The aerodynamic model is defined in LauMBS by specifying the aero coefficients (e.g. drag force, total lift force, pitch moment, etc.).
Each coefficient can be defined as a function of other independent variables such as Mach number, total angle of attack, altitude, etc.
The node where the aerodynamic loads are applied does not represent the vehicle centre of pressure but it is a fixed node on the launcher structure. Additional transport moments are automatically computed to compensate the difference between the centre of pressure and the aerodynamic node.

8.2. Distributed aerodynamics

Distributed aerodynamics means that the aerodynamic force and moment are distributed along the length of the launcher structure. LauMBS applies 30 nodes along the length of the vehicle, from the nose to the bottom as shown in Fig. 9.

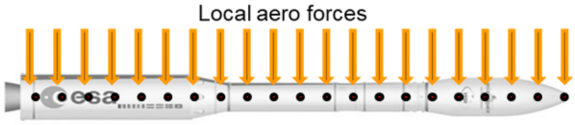

Figure 9. Aerodynamic nodes distributed along the vehicle structure

The following aerodynamic coefficients are required:

- axial force coefficient;
- total normal coefficient;
- pitch moment coefficient.

The coefficients must be function of the axial position, the Mach number and the total angle of attack.
Each node on the structure will experience a different velocity, local angle of attack and aerodynamic loads, as shown in Fig. 10. The sum of all the forces and moments on every node, is therefore different from the non-distributed model computation, because a more realistic behaviour of the mechanical structure is here considered.

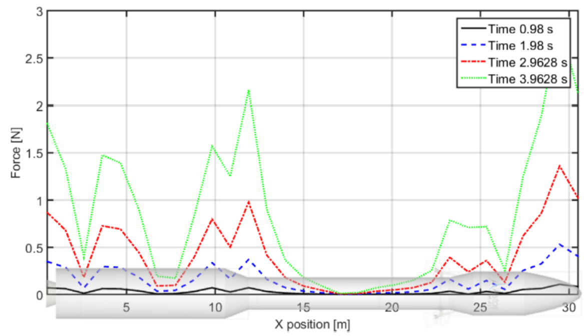

Figure 10. Local aerodynamic forces along the length of the launcher structure and function of the simulation time.

The distributed aerodynamics is a key feature for the simulation of flexible launcher structure where the local mechanical properties are influenced also by the material elastic deformations.

9. CONCLUSIONS AND FUTURE DEVELOPMENTS

LauMBS tool is a multidisciplinary tool for performing mechanical design and verification of launchers during the ascent flight and payload injection. The dynamic coupling of a multibody software (DCAP) and a GNC and trajectory optimisation oriented tool (ASTOS) represents the most advanced launcher simulator on the market nowadays. Future improvements of the software features will extend the capabilities to reproduce even more detailed scenarios.

Additional investigations of the sloshing models are required in order to reproduce the liquid dynamics in spinning rocket, which is not covered by the traditional spring-damper models.

The DCAP flexible analytical beam is a powerful starting point to model vehicle elasticity during the flight. However, for a finer tuning of the mechanical behaviour, advanced FEM models must be used. DCAP allows already an interface with NASTRAN flexible models, therefore this feature could be easily extended to the LauMBS framework.

A part from spinning rocket, launchers need a controller to fly and maintain the desired trajectory. The controller in the loop feature of ASTOS will be extended to LauMBS, allowing the simulation of the complete flight scenario.

Even if LauMBS software has been developed for a very specific purpose such as launch vehicles design and simulation, the tool could be expanded also to other broader applications:

- docking and deployment of solar panels and antenna simulations;
- robotic arms design and analysis;
- satellite dynamics prediction.

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