ESA LAUNCHER FLIGHT DYNAMICS SIMULATOR USED FOR SYSTEM AND SUBSYSTEM LEVEL ANALYSES

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ABSTRACT

Virtual simulation is currently a key activity that supports the specification, design, verification and operations of space systems. System modelling and simulation supports in fact a number of use cases across the spacecraft development life-cycle, including activities such as system design validation, software verification & validation, spacecraft unit and sub-system test activities, etc. As the reliance on virtual modelling, simulation and justification has substantially grown in recent years, a more coordinated and consistent approach to the development of such simulation tools across project phases can bring substantial benefit in reducing the overall space programme schedule, risk and cost.

Taking advantage of ESA Structures & Mechanisms division strong expertise in dynamics (multibody software) and, in particular, in launch vehicle flight dynamics, a generic flight simulator has been built to simulate a wide variety of launch vehicle dynamics and control problems at "system level" since 2001. The backbone of the Flight Dynamics Simulator is DCAP (Dynamic and Control Analysis Package), a multibody software, developed by ESA together with industry, with more than 30 years heritage in Space applications. This software 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 structural systems subjected to possibly time varying structural characteristics and Space environmental 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) behaviour, n being the number of system degrees of freedom. A dedicated symbolic manipulation pre-processor is further used in the coding optimization. With the implementation of dedicated interfaces to other specialised software (such as NASTRAN, CATIA, Matlab/Simulink,...), it is possible to reproduce, with a quite good level of details, most of the key subsystems (such as trajectory, structures, configuration, mechanisms, aerodynamics, propulsion, GNC, propulsion,...) of the launcher in a single simulation.

Taking advantage of Multibody approach, this simulator has been easily retuned in order to be used in some CDF studies on new launch vehicle feasibility concepts. Furthermore, the simulator has been adjusted to tackle specific events, such as multi-payload separation dynamics (Swarm & Galileo), thrust vector control subsystem studies (GSTP3, GSTP4 & VEGA), lift-off analysis (VEGA), general loads (VEGA). In this paper, an overview of the flight dynamics simulator capabilities is presented by illustrating the VEGA example.

BACKGROUND

The problem of dynamics of multiple bodies within the atmosphere is complex and challenging [1-2]. One problem that has received significant attention in literature is that of store separation from aircraft: NASA studies on stage separation of multi-stage reusable launch vehicles date back to the 1960s [3-4]. Moreover, NASA’s Next Generation Launch Technology (NGLT) Program identified multi-body stage separation analysis tools as one of the critical technologies needed for the successful development and operation of next generation multi-stage reusable launch vehicles [5-6].

Virtual simulation is currently a key activity that supports the specification, design, verification and operations of space systems. System modelling and simulation supports in fact a number of use cases across the spacecraft development life-cycle, including activities such as: system design validation, software verification & validation, spacecraft unit and sub-system test activities, etc. As the reliance on virtual modelling, simulation and justification has substantially grown in recent years, a more coordinated and consistent approach to the development of such simulation tools across project phases can bring substantial benefit in reducing the overall space programme schedule, risk and cost [7-9].

ESA LAUNCH FLIGHT DYNAMICS SIMULATOR

Since 2001, ESA Structures & Mechanisms division (TEC-MS) has dedicated an important amount of energy in developing a solid knowledge in launcher flight dynamics [10]. Using multibody software, which can model the dynamic behaviour of interconnected rigid and/or flexible bodies, each of which may undergo large translational and rotational displacements, it is possible to assess and verify performances at system level. More in detail, launcher flight dynamics analysis allows to verify whether the selected launch vehicle design is able to accomplish the mission objectives taking into account the output information provided by all other subsystems such as Trajectory, Structures, Mechanisms, Aerodynamics, Propulsion, GNC etc. In particularly, non-linear dynamic simulations have been run in order to assess stability in nominal and off-nominal condition, TVC angular deflection and general loads.

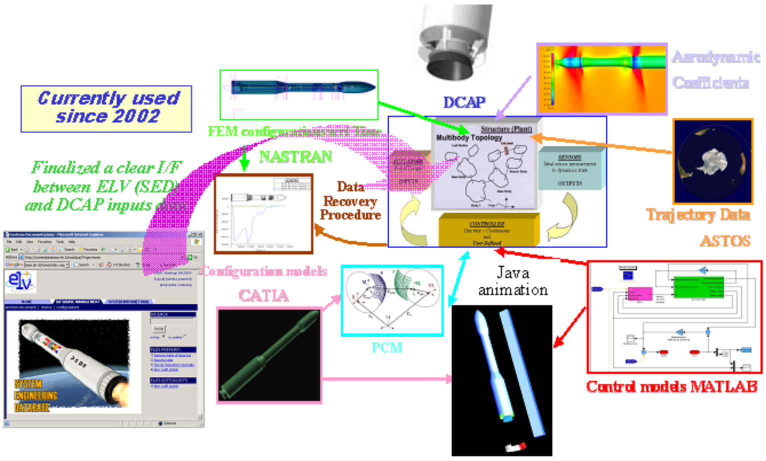


Fig. 1 VEGA-DCAP-sim overview

Taking advantage of the strong know-how in dynamics, coming from long R&D activities in Multibody Dynamics [11], specific launcher flight dynamics tools (VEGA-DCAP-sim in Fig.1) was developed for different ESA projects in order to investigate not only flight dynamic effects for VEGA Support and CDF LV studies, but also local analyses (such as gust response, lift off, multi-payload separations) for GSTP3/GSTP4 Ariane 5 TVC, Swarm Support, Galileo IOV & IOF Support, IXV support.

Furthermore, multibody software is gaining importance also in the difficult area of coupled load analysis [12], because it allows a much faster and malleable approach when compared to the classic FEM based procedures.

What Makes it Unique

The backbone of ESA Flight Dynamics Simulator is DCAP (Dynamic and Control Analysis Package), a multibody software (Fig.2) developed by ESA together with industry [13-14], with more than 30 years heritage in Space applications. This software 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 structural systems subjected to possibly time varying structural characteristics and Space environmental 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) behaviour, n being the number of system degrees of freedom. A dedicated symbolic manipulation pre-processor is further used in the coding optimization in order to allow real-time simulations.

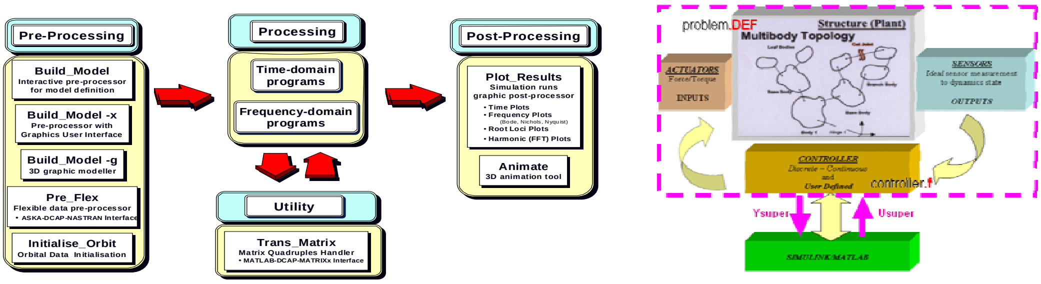


Fig. 2 DCAP features overview

The modelling capability is completed with the possibility of user-defined environment, allowing for modelling of specific control feature not directly included in the dynamic package's library. For the latter control modelling, straightforward interface with Matlab/Simulink exists.

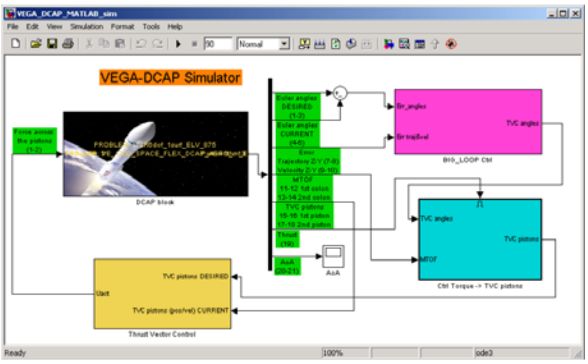


Fig. 3: DCAP IF to MATLAB-Simulink (co-simulation)

In a nutshell, the main characteristics of ESA launcher flight dynamic simulator (VEGA-DCAP-sim) are:

- Multibody-based (easy to model the dynamics of “complex” launchers) [10]
- Flexible or rigid bodies both with time varying characteristics [15]
- LV flight Dynamics-Control interaction (directly imported in Matlab) [15]
- Environment modelling for Flexible launcher including external disturbances [16]
- Easy modelling non-linear effects (as misalignment, inertia influences, crosstalk effects, sloshing.)
- Easy modelling of dynamic transitions (lift-off analysis, stage and payload separations, …) [17-18]
- High degree of compatibilities with different software packages

Launch vehicle dynamics having multiple nozzles can be easily simulated using multibody capabilities with minimal workload. An example is reported in Fig.4, which represents an example configuration of future launcher study. The first stage consists of 4 boosters and a main motor controls 5 nozzles, which can be tilted independently. Despite being a rather complex to represent, the system proved relatively straightforward to model using the multibody tool, Therefore, more time was invested to investigate the best philosophy to command the individual nozzles, which could meet the strict requirements placed on the control part.

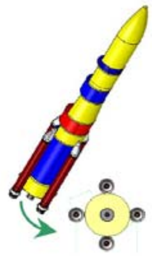


Fig. 4: Launcher with multiple nozzles

Launcher Flight Dynamics Simulator for CDF studies

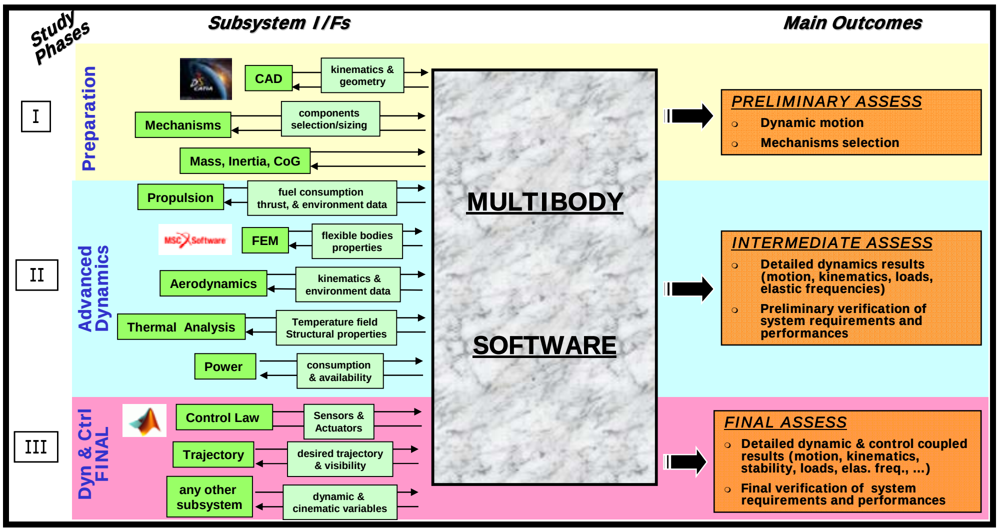


Fig. 5: Multibody expertise in CDF environment

Lately, based on past successful experiments [16-19], the advantage of multibody software has also been made available to ESA Concurrent Design Facility (CDF) studies (Fig.5). Indeed, since CDF applies the concurrent engineering method to the design of future space missions [20], the use multibody software is a key tool for analysing performances at system level, while taking into account simultaneously several subsystems.

In the next figures launch flight dynamics simulation applications are briefly presented, which highlight the interfaces with other subsystems and some typical results.

APPLICATIONS OVERVIEW

System level analysis

Typical non-linear time simulation results for 1st stage 3D non-linear trajectory simulation in nominal condition are reported in Fig.6. Off-nominal conditions (such gust/wind profiles) can be easily simulated as well.

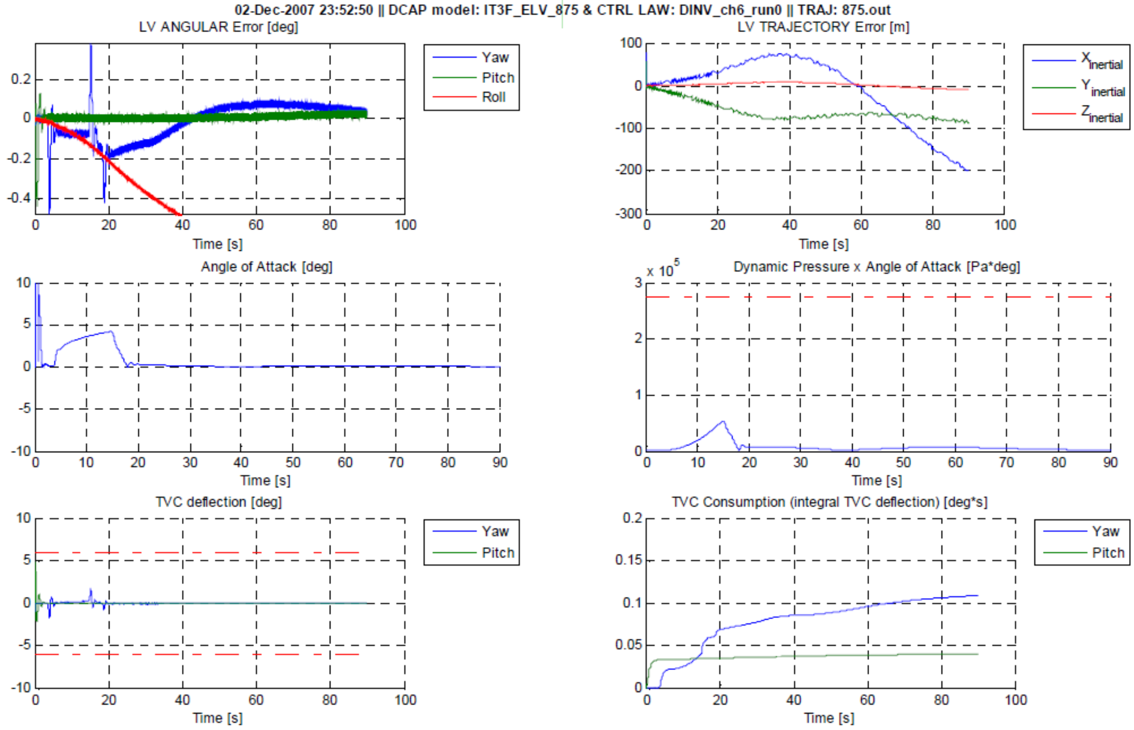


Fig. 6: launcher flight simulator results in CDF environment

Besides flight dynamic results, the simulator is able to compute additional parameters such as accelerations and loads at any point of the vehicle. An example is shown in Fig.7.

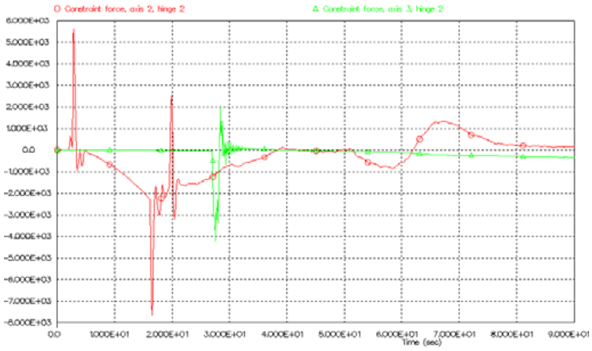


Fig. 7: Constraint forces in lateral directions at nozzle pivot-point [N]

A useful capability allows DCAP to perform parameter sensitivity analysis (based on MonteCarlo): any parameter of the simulation, both in the dynamic and in the control sector, can now be substituted by means of randomly generated data, in accordance with a user-defined standard probability distribution (such as linear, uniform or Gaussian).

Subsystem level analyses

The simulator can be easily adjusted to tackle specific events, such as: multi-payload separation dynamics, thrust vector control subsystem studies, lift-off analysis, general loads,…
Hereby a brief overview of such local analyses is presented.

- *Thrust Vector Control*

  The simulator can be also used to investigate more in details the coupling between the thrust vector control, which is in charge to steer the nozzle following the flight controller requests, and the whole vehicle structures [10]. Linear analysis can be easily implemented in DCAP by means of numerical linearisation of the non–linear dynamic equations around a particular equilibrium state. The results reported in Fig.8-9 are computed having the control system in open loop and the thrust vector control in closed loop.

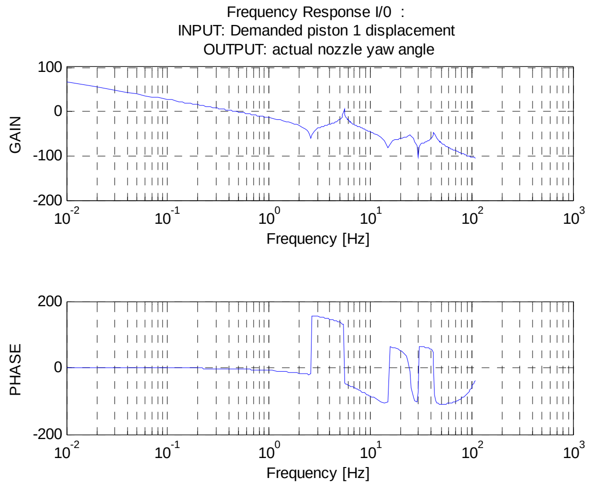


Fig. 8: Frequency response from demanded actuator_1 displacement to actual nozzle yaw angle

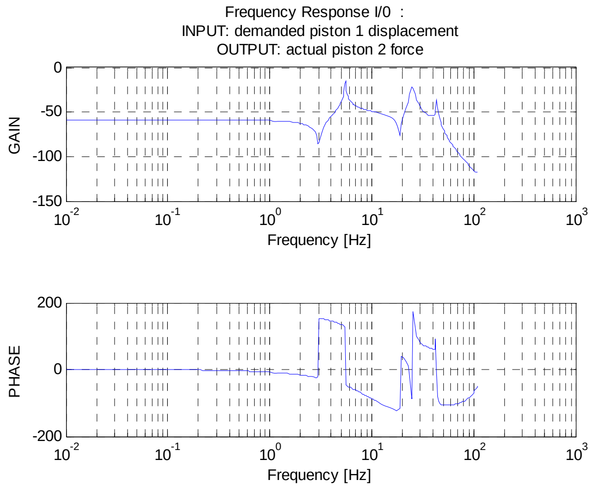


Fig. 9: Frequency response from demanded actuator_1 displacement to actual actuator_2 force

Furthermore, nonlinear time analyses can be also highlight the effect on the vehicle structures due to nozzle activation profile, when a more detailed thrust vector control mathematical model is considered (Fig.10-11).

Fig. 10: VEGA thrust vector control overview

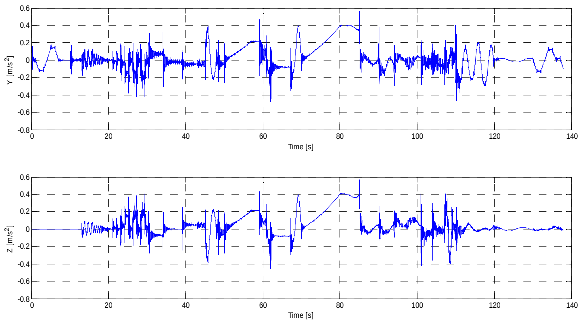


Fig. 11: Typical induced acceleration of a specific location

- *Multi-payload Separation*

  Also, the simulator has been adjusted to tackle multi-payload separation dynamics (Fig.12-15).
  Two different analyses, SWARM (a formation of 3 satellites for Earth Observation Mission) and Galileo (satellites for Navigation Mission), are presented in [17]. Multibody software's versatility allows for easy modelling of quite

sophisticated separation mechanisms, including pusher/umbilical dynamics, different potential launch vehicle and various orbital environment disturbances.

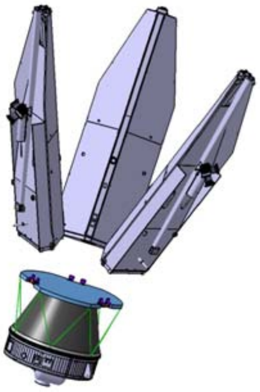


Fig. 12. Separation of the 3 Swarm satellites

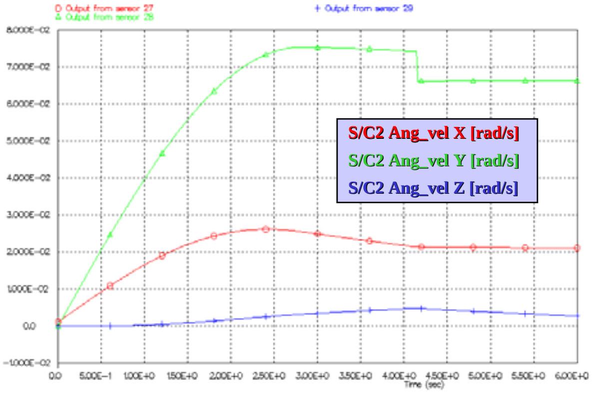


Fig. 13. Angular rate of ejected satellite in staggered separation scenario

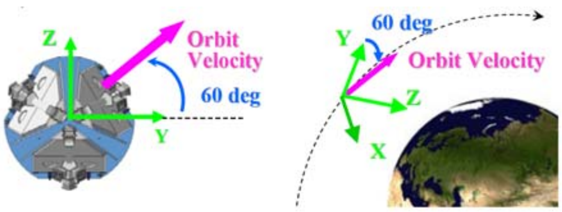


Fig. 14: Ejection in orbit

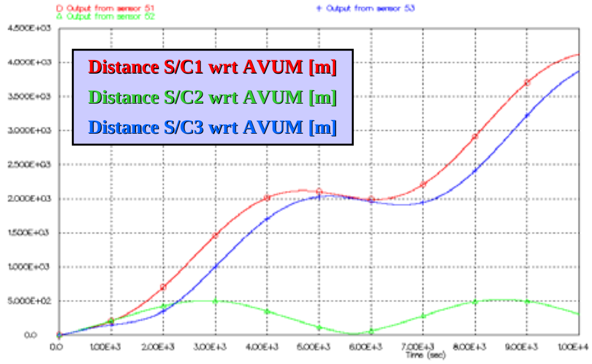


Fig. 15. Relative distance between the satellites and launcher

- *Complete lift-off phase analysis*

  To study the complete lift-off phase is important to be able to simulate all sub-phases (stand-by on ground, detachment from the LV pad, disengagement and capture phase) using a single model, in order to avoid any energy loss, which may occur when each sub-phase is independently studied [18]. For this analysis, the ESA VEGA-DCAP-sim simulator has been adapted to take into account the propellant dynamics and the effect of the nozzle (Fig.16), which is modelled as a separate rigid body, hinged to the main launcher at the pivot point. The structural stiffness and damping properties of this hinge are taken into account as well. Furthermore, specific different external disturbances (such as blast waves and vortex shedding) are also modelled. Due to the important disturbance effect of the latter, an Anti Vortex Shedding (AVS) device was added (Fig.17). This device is simulated by inserting several parallel contact elements, having non linear stiffness characteristics, between the launcher and the LV pad (Fig.18). Finally, after separation from the launch pad, the control is switched on to stabilize the vehicle and to avoid contact with the tower (Fig.19).

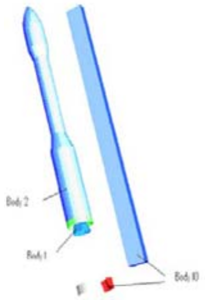


Fig.16: VEGA-DCAP-sim topology for lift-off analysis

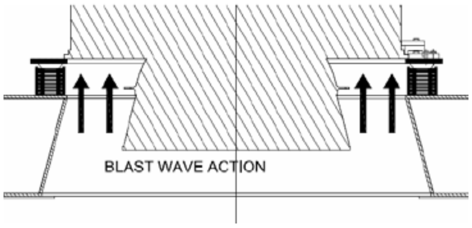
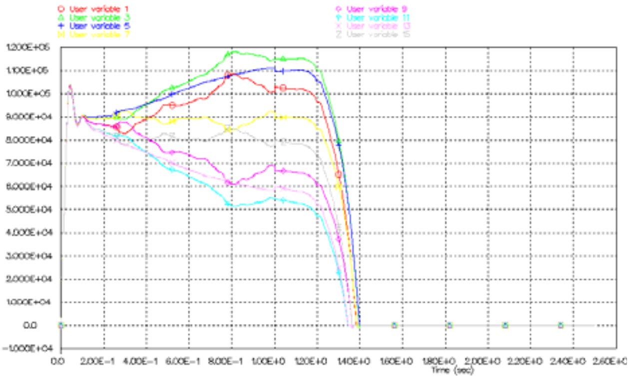


Fig.17: AVS device sketch



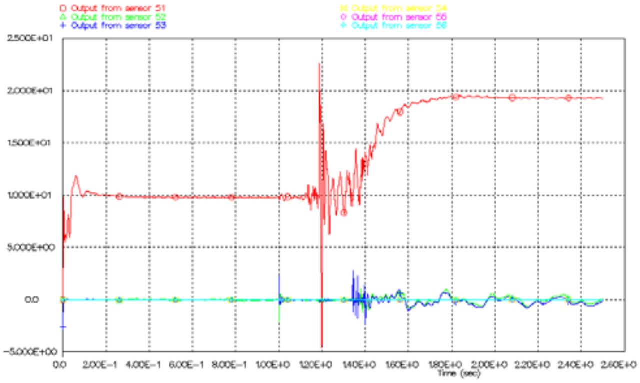
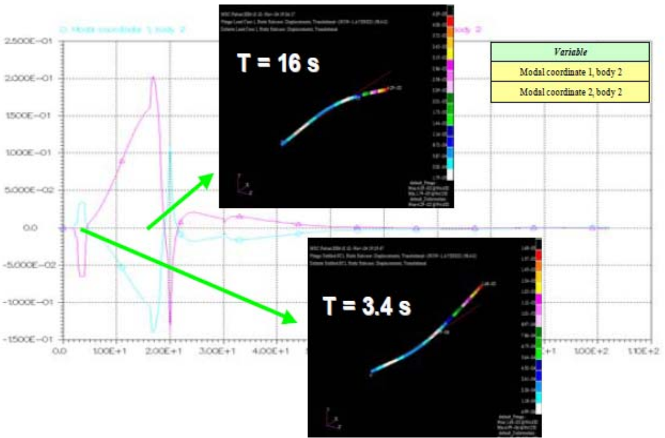


Fig.18: Forces at I/F points [N] in off-nominal condition

Fig. 19: Pivot point accelerations in off-nominal condition

- *General loads*

  A data recovery procedure (DRP) has been implemented in DCAP and validated using ATV finite element model [17]. This procedure allows post-processing the DCAP results in Nastran and computing internal loads. Fig.20-21 represent the typical results of the VEGA launcher using a beam model. Some results, not presented, are available for the 3D VEGA FEM model as well.



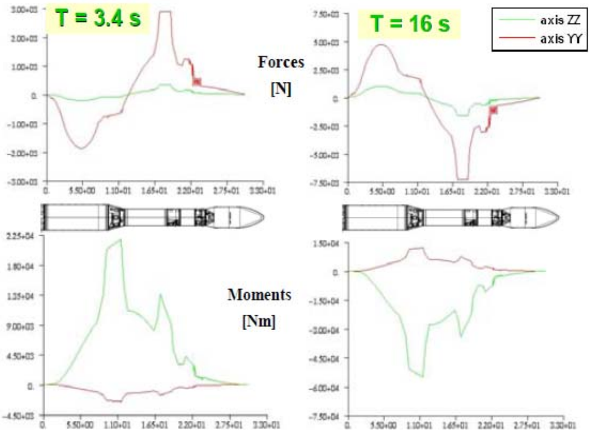


Fig. 20: 1st and 2nd modal coordination behaviour and VEGA deformation for two different flight conditions

Fig. 21: DRP Forces and moments results for two different flight time

CONCLUSIONS

In conclusion, the ESA Launcher Flight Dynamics Simulator represents an important successful story of a European software package, internally developed by the European Space Agency with the support of Alenia Spazio Torino.
Its peculiar generic modelling capabilities and computational speed are strong assets of the simulator, enabling real time comprehensive simulation of an entire multi-stage launcher along all the different phases of the launch.
The high degree of interface with different specific tool packages allows for exchanging data and cooperating with other disciplines at the same time in a reliable and user-friendly environment.

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