VEGA LV Qualification Process: GNC aspects on HWIL Testing and Analysis

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Abstract

The present paper is aimed at providing a technical overview of the final step of the Flight Program Software Alternative (FPSA) qualification process, that consists in the Hardware-in-the-loop (HWIL) simulation campaign, addressed to demonstrate the correct functioning of the software in which the GNC (Guidance, Navigation and Control) algorithms are embedded.
The HWIL test analysis, from a GNC point of view, is focused above all in investigate and evaluate the effects of the introduction of the real hardware in the simulation loop, in particular in non-nominal (*scattered*) conditions, both in terms of representativeness of the models in the numerical (SWIL, Software-in-the-loop) campaign, both in terms of introduction of physical effects (delays and non linearities) in the control chain that can eventually lead to a limit behaviour of the actuators.
In the first section of the document a short presentation of the FPSA program and the SW validation logic are reported. The second part is focused on the criteria on which the scattered test cases to be run in the frame of HWIL test campaign are defined, that varies differently according to the various GNC aspects on which the analysis is aimed to. Successively, all the different setup configuration are defined, that ranges from the simplest Processor-in-the-loop (PIL) configuration, in which just the real OBC is in the simulation loop, up to a full HW configuration that has the highest level of flight representativeness. Finally, a practical example coming from the test campaign activities is reported in order to demonstrate the full flow of the process.

List of acronyms

AVUM	Avionic Upper Module
EGSE	Electric Ground Segment Equipment
FDIR	Failure Detection Identification and Recovery
FPS	Flight Program Software
FPSA	Flight Program Software Alternative
HF	High Frequency
HWIL	Hardware in the loop
LF	Low Frequency
LV	Launch Vehicle
MC	Montecarlo
MFU	Multi-Functional Unit
NAM	Neutral Axis Maneuver
OBC	On-Board Computer
PIL	Processor in the loop
P/L	Payload
RACS	Roll and Attitude Control System
SRM	Solid Rocket Motors
SWIL	Software in the loop
TVC	Thrust Vector Control
TWD	Tail Wag Dog
VESPA	VEGA Secondary Payload Adapter

1. Introduction

The second launch of VEGA LV, first flight in the frame of VERTA program, that successfully took place on the last 6th May 2013, represented a corner-stone in the development of the European Launch Vehicle as for the first time a completely new flight program software, all developed internally, was used aboard.
The FPSA program started with the aim to produce a new software suitable for a wide range of mission functionalities like those VEGA is projected to, with substantial difference with respect to the FPS that flew on the qualification flight.
Even based on the same layers organization, several modifications have been introduced in the FPSA software, mainly regarding the part related to GNC functions, as:

- the Flight Management functionalities are separated: the tests versus time marks are no more performed inside the functions but located in a dedicated module, responsible of the timeline generation;
- each function is organized in cyclic and sporadic activities, the former being executed recursively in the algorithms and the latter being linked to the occurrence of well-defined conditions;
- the multi-PL functionalities (adaptation of timeline, maneuvers) have been all implemented, that also take into account the presence of the VESPA, as reported in [1] ;
- new self-developed RACS algorithms are implemented (refer to [2]) ;
- the guidance algorithms changed in order to optimize the NAM (manoeuvre for impact point of third stage Z9) and the AVUM boosted phase, including the direct re-entry of upper stage;
- homogenization of Mathematical Library;
- the FDIR management in case of accelerometer failure is executed in a separate module located in the IRS function and not as exceptions in the body of each function; moreover, a so-called synthetic IRS is implemented to improve not-nominal functioning performances.

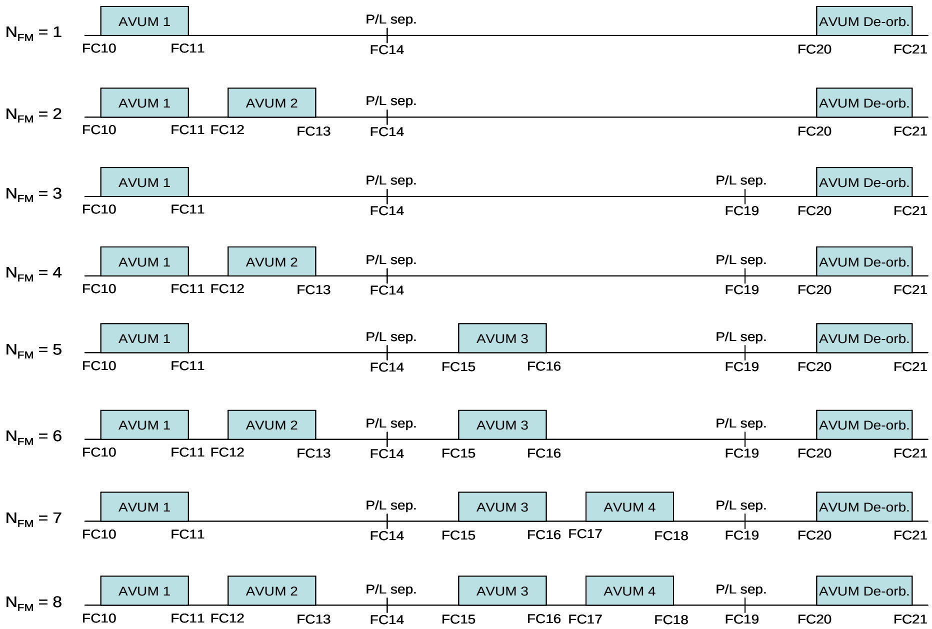

Figure 1 VEGA LV mission scenarios

The validation process of the algorithmic part of the SW is explained in the following section.

1.2 FPS-A Validation Logic

The FPS-A validation process, from an algorithmic point of view, can be summarily divided into two parts: first of all, a series of SWIL testing activities are performed in order to assess the correct behaviour of the GNC in an ideal simulation environment in which all the inputs/disturbs are a well a priori identified.
The results obtained in this phase are then compared with those obtained in the HWIL testing phase, in which the representativeness of the simulation environment is increased by the introduction of real HW components that, by themselves, add a certain degree of uncertainty on the tests.
The SWIL validation consists in two steps: first of all, a Performance Assessment for each GNC function (Guidance, Navigation, TVC, RACS, Flight Management) has to be performed, in which the requirements defined by the

Avionic Specification are to be verified with the associated level of probability P and confidence level C. The number of simulation to be run depends on P, C and by the definition of the requirement itself, so that both probabilistic and deterministic approaches can be used, that consists in:
- a MC campaign, in which the parameters are randomly scattered, is performed in order to go through different combination of the variables;
- a set of single runs are selected, in which the parameters are varied in order to be representative of the worst case conditions that the LV can face. The choice of this set will be detailed in §1.4.

Furthermore, the performance of the various GNC functions are evaluated not on the same mission, but over different sizing scenarios.
Once for each discipline all the expected performances are achieved, a Numerical Validation consisting in running simulations of a complete mission is carried on, that involves all integrated GNC functions using an emulator of the FPSA. The success criteria of this phase is to demonstrate the correct interface between the functions and possibly (even if not mandatory) to confirm the requirement satisfaction (where they are applicable).
At the end of the SWIL validation, the HWIL test campaign has to demonstrate that the introduction of real HW let the laboratory test runs to be as close as possible to those performed in SWIL, analysing the possible deviations with respect to them and justifying the differences that can be eventually found.

1.3 Simulation environment

The SWIL/HWIL activities are based on the use of two different simulators, called respectively VEGAMATH ® and VEGASIM ®. VEGAMATH is a non - real time simulator fully developed in a Matlab - Simulink environment whose core is represented by the 6DoF model of the LV, that takes into account the particular characteristics for the current flight (that is, P/L data, motor curves, MCI prediction, bending modes) and in which the equation of LV motion are represented together with the external environment. This is interfaced with the actuators models (TVC, RACS) and with an FPSA emulator, written in ADA language, and linked in closed loop.
VEGASIM ® represents an extension of VEGAMATH ®: it runs in real time and offers the chance to explore a certain number of configurations being able to interface with the real HW components (in a similar way to those reported in [3]), in a way to gradually increase the degree of representativeness of the simulation environment (see Figure 2).
In the simplest configuration (*PIL configuration*) it is than interfaced with the OBC where the FPSA is loaded by means of an EGSE emulator (for the initial loading and synchronization), keeping the model of TVC, MFU (Multi Functional Unit, that is the unit in charge of physically command the actuation to the control subsystem), IRS (Inertial Reference System) . This configuration allows comparing the effect of the use of the real FPSA over the control actuators, verifying that no problems are present in the implementation of the software.
A more complex configuration, called *Configuration 5*, is obtained when the real IRS and MFU are put in the loop together with the AVUM TVC; in this case, the OBC is fed with the attitude data coming from the real inertial platform, present on the communication bus, and gives its commands to the real actuator. This configuration setup allows evaluating the impact of the introduction of delays inside the simulation loop due to the IRS computation and actuations measurements by the potentiometers, together with effect due to the TVC.
The last step, that offers the highest representativeness of the LV, is given by the *Configuration 7,* in which all the real TVC are used. It has to be noted that a further configuration, called *Full Avionics Configuration,* is present but from a GNC point of view it is equivalent to the configuration 7 as the modification just includes the use of batteries and other HW related components.

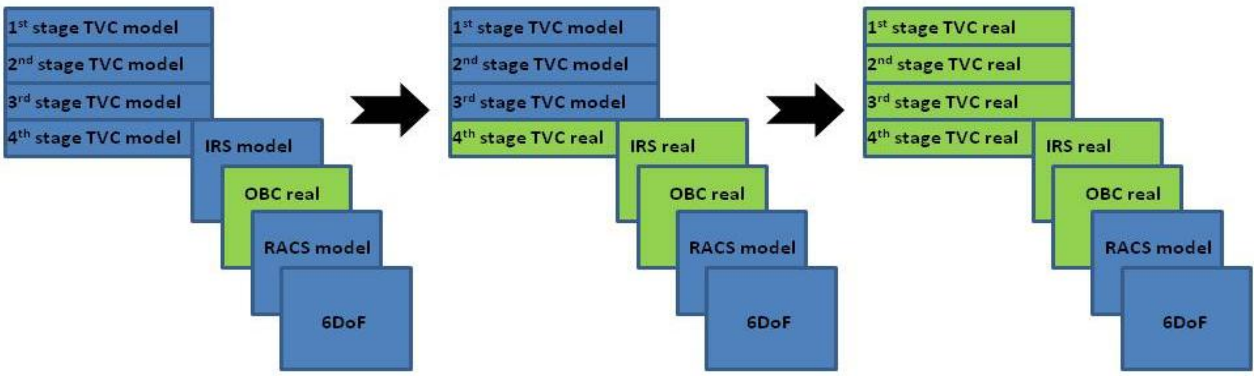

Figure 2 VEGASIM configuration schematic representation

In spite of the presence of real elements, the HWIL set up for can't be fully representative of the reality as:
- actual IRS is replaced by a laboratory IRS in which sensors are simulated;
- electro-valves and pyro-devices are simulated;
- physical TVC actuators are not exactly the flight equipment (nozzles, skirts and pressure conditions are of the *maquette*, not of flight);
- nozzle inertia effect (TWD effect) is not faithfully represented since deflection acceleration is not output of real TVC;
- several devices of the set up (various computers, potentiometers, optical and electrical lines and associated filters) are not present in flight and introduce additional delays in the control chain.

1.4 Worst Case Identification

The identification of Worst Cases to be performed in the frame of both SWIL and HWIL test campaign is different depending on the topic to be verified: for control topics, it is based on qualitative consideration about the main dimensioning scenario that the LV can face; for guidance topics, it comes from the result of MC analysis as the worst values for navigation and guidance algorithm can't be determined *a priori*. As last instance, the FDIR test cases are individuated injecting the error in particular phases considered as critical for the mission.
The logical flow starts with the individuation of a number of parameters whose variation can lead to evident deviations with respect to nominal performances over particular flight phases; then they are opportunely combined in order to perform the minimum number of runs.
The main parameters that are commonly scattered are:

a. A_6 coefficient (aerodynamic efficiency), related to the aerodynamics instability:

$$A_6 = \frac{p_{dyn} \cdot S_{ref} \cdot C_n \cdot L_A}{I_{yy}} \tag{1}$$

b. K_1 coefficient (*TVC control efficiency*), related to the TVC effectiveness and linked to the motor thrust T, the inertia I_{yy} and the position of LV center of gravity L_T:

$$K_1 = \frac{T \cdot L_T}{I_{yy}} \tag{2}$$

c. $K_{1R,n}$ coefficient (*RACS control efficiency*), related to the RACS effectiveness and linked to the n-th thruster impulse bit I_{bit}, the inertia I_i and arm L_i with $i = x, y, z$ axis:

$$K_{1R,n} = \frac{I_{bit,i} \cdot L_i}{I_i} \tag{3}$$

d. Bending modes (only SRM phases)
e. Sloshing modes (only AVUM phase)
f. Atmosphere and winds
g. Disturbing torques: roll and separations
h. Actuators uncertainties (TVC and RCTs)
i. IRS noise, scale factor, bias, drift and initial alignment errors

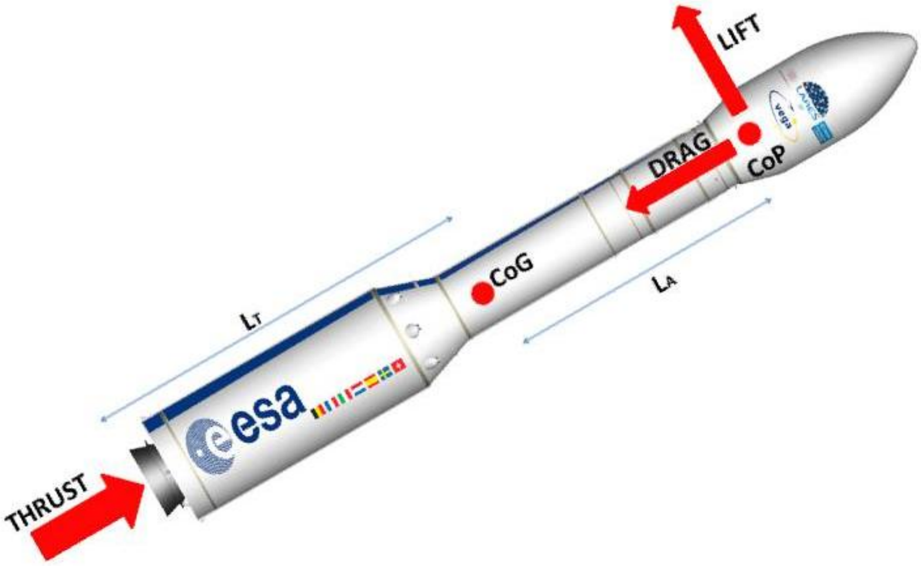

Figure 3 Qualitative scratch of forces distribution over LV

A series of eight WCs is chosen for control topic considering the effect that each of them can induce during the different flight phases.
The aerodynamic parameter plays its role mainly during the atmospheric flight of the 1st and 2nd stages (P80 and Z23 phases), being influenced both by the LV constructive values (inertia and shape), and both by atmospheric variables (air density), as by definition

$$p_{dyn} = \frac{1}{2} \rho \cdot \mathrm{v}^2 \quad \textbf{(4)}$$

It should be noted that, on the converse, K_1 just depends from the LV mass properties (as defined in eq.1) and from the motor characteristics, as in turn the thrust T is defined as:

$$T = ISP \cdot t_c \cdot \dot{m} \quad \textbf{(5)}$$

where t_c is the combustion time, $\dot{m}$ is the mass flow rate and ISP is the specific impulse.
The four combinations of these two coefficients are representative of the boundary (worst) conditions that the LV can face: considering the ratio between A_6 / K_1, it can be maximized or minimized by considering opposite directions of the scattering (A_6 max and K_1 min and vice versa); in turn, also the effect of concordant verse of variation is considered. It should be noted that, in general, low inertia means more effect of the disturbances.
The different combination are also considered to be subject to different external disturbance such as dimensioning winds (both at liftoff and during the flight) or torques induced by the propulsion or aerodynamics, in order to evaluate the behaviour of the LV. Moreover, also the structural component is to be taken into account as the bigger is the mass and the length of the body, the greater is the impact of bending modes over the control performances when they are considered not nominal. Substantially, only the K_1 parameter influences the control during the third stage flight (Z9 phase), being already considered an extra-atmospheric phase and thus not influenced by the aerodynamics.
The TVC control is moreover influenced by the transfer function considered in the model, depending on the phase (PH) and gain margins assigned (considering as critical both the case LF and HF).
As far as RACS control is concerned, it has to be underlined that the scattering of parameter $K_{1R,n}$ defined in (eq.3), differently from FPS baseline, has an impact also in this phase because of the roll control phase implemented in the FPSA algorithms, that directly influences the separation condition of the stage.

Besides this scattering, the performances of the control are verified by increasing the sloshing effect that acts as a disturbance torque to be compensated; also in this case, the disturb has to be considered in its extreme condition, that is both with the maximum amplitude or the maximum frequency, obtained by increasing or decreasing the amount of sloshing mass considered in the model, thus inducing different reaction (greater number of activation or greater thrust to be delivered).
As far as the guidance performances are concerned, the worst conditions are easily individuated to be those corresponding to the shortest and longest first AVUM propelled phase duration: the first case can to a non-optimal compensation of all the guidance parameters, whereas the second implies a higher propellant consumption.
These conditions are obtained by considering a scattered solid motor phase, both in terms of motors performances and LV mass parameters; the values to be assigned is round looking at the results coming from the MC campaign, as a priori a linear relation can't be found.
Moreover, these tests are also combined in order to achieve the limit condition on orbital accuracy, both in terms of apogee and inclination error. These are obtained by imposing a certain scattering (still coming from the MC campaign) on IRS parameters: in the first case, the effective parameters are those related to the bias and scale factor of the accelerometers/gyrometers, whereas in the second case it is the initial misalignment that plays the fundamental role.

The FDIR topic is not properly related to the performances, but mainly to the robustness of GNC algorithms when working in not-nominal mode. Depending of the type of mission and its main features (see Figure 1), i.e. the number of boosts, kind of manoeuvre and constraints, a number of tests is set to reach the conditions imposed on AVUM/RACS propellant (exhaustion) or LV dynamics (not physical attitude/attitude rate) to make the FDIR mode switched on. The scattering figures that lead to these conditions are well besides the 3-σ that is used to the requirement limits, so that also some out-of-requirement is accepted to declare the goodness of the test. Moreover, also an HW failure is simulated on the accelerometers in certain critical phases (separations).

TEST	Main Points	P80	Z23	Z9	AVUM PROP	AVUM BALLISTIC	Main aspects to check
C1	Wind at Lift-off Min RACS efficiency P80 LF, Z23 HF, Z09 HF, AV HF	(A6/K1) max TVC_LF Bend Max	(A6/K1) min TVC_HF Bend Min	K1 max TVC_HF Bend Max	K1 min TVC_HF Slosh (Max freq)	RACS K1 min Slosh (Max freq) Max offsets	Lift off RACS TVC
C2	Wind at Separation Min RACS efficiency	(A6/K1) max TVC_Nom Bend Max	(A6/K1) min TVC_Nom Bend Min	K1 max TVC_Nom Bend Max	K1 min TVC_Nom Slosh (max freq.)	RACS K1 min Slosh (max freq.) Max offsets	Separations RACS
C3	Wind at max PDyn Min RACS efficiency P80 PH, Z23 PH, Z09 PH, AV PH	(A6/K1) max TVC_PH Bend Min	(A6/K1) min TVC_PH Bend Min	K1 max TVC_PH Bend Min	K1 min TVC_PH Sloshing Nom	RACS K1 min Sloshing Nom Max offsets	RACS TVC
C4	Max roll (wind at low quote) Min RACS efficiency P80 MaxRoll; IRS scat Max Orbit Inclination	A6 max / K1 max TVC_NOM Bend Max	A6min / K1 min TVC_Nom Bend Min	K1 max TVC_Nom Bend Min	K1 min TVC_NOM Sloshing Nom	RACS K1 min Sloshing Nom Max offsets	Orbital accuracy TVC RACS
C5	Wind at Lift-off Max RACS efficiency P80 HF, Z23 LF, Z09 LF, AV LF	(A6/K1) min TVC_HF Bend Min	(A6/K1) max TVC_LF Bend Max	K1 min TVC_LF Bend Min	K1 max TVC_LF Slosh (Min freq.)	RACS K1 max Slosh (Min freq.) Max offsets	Lift off RACS TVC
C6	Wind at Separation Max RACS efficiency	(A6/K1) min TVC_Nom Bend Min	(A6/K1) max TVC_Nom Bend Max	K1 min TVC_Nom Bend Min	K1 max TVC_Nom Slosh (Min freq.)	RACS K1 max Slosh (Min freq.) Max offsets	Separations RACS
C7	Wind at max PDyn Max RACS efficiency P80 PH, Z23 PH, Z09 PH, AV PH	(A6/K1) min TVC_PH Bend Max	(A6/K1) max TVC_PH Bend Min	K1 min TVC_PH Bend Min	K1 max TVC_PH Sloshing Nom	RACS K1 max Sloshing Nom Max offsets	RACS TVC
C8	Max roll (wind at low quote) Max RACS efficiency P80 MaxRoll; IRS scat Max Orbit Apogee	A6min / K1 min TVC_Nom Bend min	A6 max / K1 max TVC_Nom Bend Max	K1 min TVC_Nom Bend min	K1 max TVC_Nom Sloshing Nom	RACS K1 max Sloshing Nom Max offsets	Orbital accuracy TVC RACS

Table 1 Control test cases

TEST	DESCRIPTION	Notes	Main aspects to check
G1	Guidance AVUM1 min duration	Over propulsion during SRM phases	Orbital accuracy; TVC; RACS; NAM It expects that an over propulsion in SRM phases is recovered on the AVUM phase and has no influence on mission.
G2	Guidance AVUM1 max duration	Under propulsion during SRM phases	Orbital accuracy; TVC; RACS; NAM It expects that an under propulsion in SRM phases is recovered on the AVUM phase and has no influence on mission.

Table 2 Guidance test cases

TEST	DESCRIPTION	Main aspects to check
FD1	Guidance: LPS exhaustion	No divergence during the mission is expected. No instability of GNC or FPSA;
FD2 FD3	Guidance: IRS accelerometers failure	
FD4 FD5	RACS control: Hydrazine exhaustion	

Table 3 FDIR test cases

2 Analysis of HW Impacts On GNC: a practical example

A practical demonstration of the impact that the introduction of the real HW can induce in the simulation results is hereafter reported, coming from one of the last HWIL campaigns performed in the frame of SW qualification before the VV02 mission. The nominal test is reported as example, even if the same consideration can be made for control tests C2, C4, C6 and C8.
A dedicated post-processing tool developed in Matlab ® allows the loading of both telemetry data and simulated variables, in order to make a qualitative comparison between the plotted curves and verifying automatically the requirement satisfaction. For each of GNC topics, a certain number of relevant parameters is presented and analysed.
The analysis of the nominal test, performed in configuration 7, had shown a qualitatively significant difference in the behaviour of TVC during the first stage flight in the steady state control phase, where a kind of low amplitude (0.01°) limit cycle is present in the laboratory test (see Figure 4).
Starting from the observation that the same test case (nominal simulation) performed in PIL configuration didn't show this kind of behaviour (see Figure 5), the cause of this phenomenon was identified in the TVC mounted in the laboratory setup. The investigation led to assess the presence of a non-linear effect inside the control loop as a pure delay, figured out in as first hypothesis, was not compatible with the other flight phases.
In dynamic system literature (see [4]), this effect is known as *backlash* and it is defined as a geometric non-linearity present in every mechanical system where a driving member is not directly connected with the driven member; this happens when a certain play in the actuator is present because of the mounting or because some modification in mechanical part (i.e. for example, the flexible joint) have been induced by the use.
The system thus results to be uncontrolled in that instances in which the gap between parts becomes effective, that is for a quick inversion of the command or for amall amplitude commands, like in the case of TVC, inducing a limit cycle whereby the system oscillates with a peak to peak amplitude that may exceed the total size of backlash gap.
This effect was not observed in all the precedent laboratory campaign and in the other stages, while it was identified in the VV01 post-flight activity, with greater amplitude (0.032°).

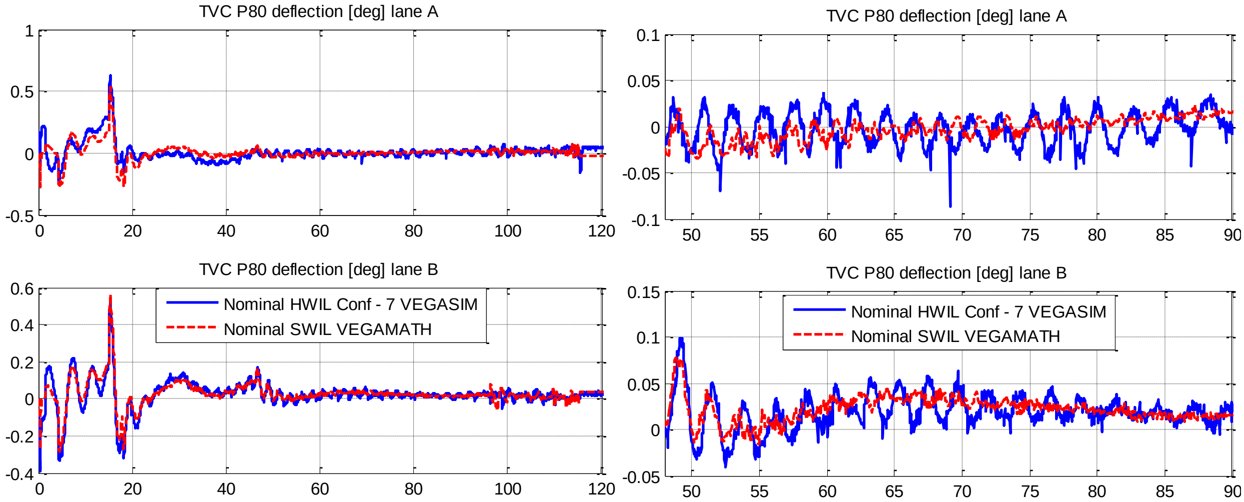

Figure 4 TVC P80 actuation profile test on configuration 7 test and zoom over steady state limit cycle

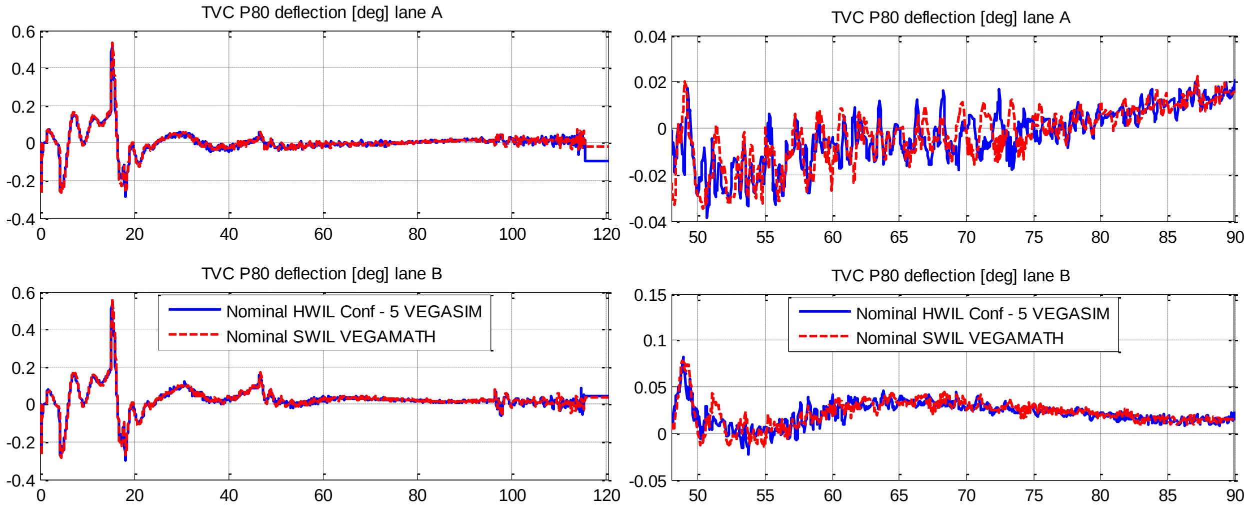

Figure 5 TVC P80 actuation profile on configuration 5 test and zoom over steady state

Starting from this evidence, the tests specified for the last HWIL campaign has been modified in order to take into account that:

- a difference between SWIL and HWIL test is to be expected even in nominal conditions, so that a certain amount of backlash is to be taken into account;
- the amplitude of the backlash is not well identified for the actuators, so that even more severe (worst) condition have to be foreseen

Thus, it has been assessed to test the behaviour of real HW when a further non linearity is introduced in the control-measurements chain in order to approximate the presence of a greater backlash value, so to sum up the backlash observed in the VV01 flight to the one present in laboratory.
Finally, the result obtained confirmed the robustness and the performances of the TVC control loop.

3 Conclusions

The present paper has illustrated the logic flow that has led to the validation of the Flight Program Software Alternative (FPSA) developed for VEGA LV.
The technical part of the document has shown the significant parameters that are taken into account in defining the test cases that have to be run in the final step of the qualification process, that is the Hardware-in-the-loop (HWIL) simulation campaign.
The effect of the introduction of the real hardware in the simulation loop, in particular in non-nominal (*scattered*) conditions, both in terms of representativeness of the models in the numerical (SWIL, Software-in-the-loop) campaign, both in terms of introduction of physical effects (delays and non linearities) has been depicted, together with the impact on the different GNC topics .
A concrete example of the working strategy has been reported. This has shown how the same simulation conditions were impacted by a different setup, inducing non-linear effect in the control chain that reflects on an evident difference in actuator profiles and thus determining a change in the individuation of the worst condition to be further tested.

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