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THE V&V PROBLEMATIC FOR LAUNCHERS: CURRENT PRACTICE AND POTENTICAL ADVANTAGES ON THE APPLICATION OF MODERN ANALYSIS TECHNIQUES

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ABSTRACT

Current launchers V&V processes typically address probabilistic time domain requirements through Monte Carlo campaigns or a set of selected worst cases while addressing frequency domain requirements through a set of predefined vertex cases. These approaches suffer inherent difficulties, such as discretization of the payload/flight-time, while most often times yielding overtly conservative results. For example, when the parameters must be considered uncorrelated, due to the need to ensure worst case margins over the full parameter scattering. This article presents an assessment of the current launcher V&V gaps and proposes a general enhanced V&V framework based on the use of modern analysis techniques.

1. INTRODUCTION

Launcher vehicles (LV) involve complex mission and system requirements, resulting in complex system architectures, software algorithms and hardware implementations. Mission critical requirements must be managed by the LV guidance, navigation and control (GNC) system during all phases of flight. And while this may not be the case, limits on current GNC performance tend to be constrained by the controller design methods, tools and processes used. Indeed, introduction of modern design techniques in the LV GNC design process have followed the establishment of more demanding requirements unachievable with more traditional methods, or rather more easily achieved and validated with the modern [1, 2].

To remain competitive it is necessary to improve the on-time launcher GNC design cycle while at the same time accounting for wider mission and payload ranges, and with increased performance and robustness characteristics. A direct axis of improvement in the GNC cycle is perceived on its verification & validation (V&V) component. Traditionally, GNC V&V is performed through Monte Carlo (MC) analyses [6, 7] in order to understand the effect of parameter uncertainties and system degradations while providing quantitative assurances (based on defined probability and confidence levels). Although the MC approach is very practical in showing the design sensitiveness to parametric variations, it has many disadvantages in as much that it relies on massive amounts of computations without guaranteed proofs on the full parameter space. To overcome these limitations many advances have been explored in the field of aeronautical and military GNC V&V based on advanced theories and tools [3, 4, 5].

For launch vehicles, the V&V needs are similarly important and it is necessary to respond not only to increasing performance demands at largely extended operational ranges within short turn-around times, but it is also necessary to have a rigorous GNC design V&V framework dedicated to account for the multivariable, uncertain, time varying and nonlinear character of launcher dynamics.

Within the frame of an ESA study entitled “Robust Flight Control System Design Verification and Validation Framework” (RFCS) work is performed with the objective of developing, demonstrating and comparing with a traditional V&V framework a new enhanced design V&V framework for application to the V&V of a complex launch vehicle. The enhanced V&V framework is envisioned to rely on the use of advanced modeling, analysis and control tuning concepts. The consortium is formed by Deimos Space S.L.U (lead, Spain), ELV (Italy), A3R (Italy) and DLR (Germany) with ample experience in launchers (i.e. ELV is the main contractor of the future European launcher VEGA [8, 9]) and advanced techniques [9, 10, 11, 12, 13, 14]. The enhanced V&V framework is expected to result in:

- Better management and improved robustness / performance margins’ assessment.
- Reduction of the technological gaps present in the current V&V process.
- Significant reduction of the V&V effort.
- Allow industrialization of the most promising V&V techniques for their use in future ESA projects.

These improvements are expected to be achieved by: (i) identifying the technological gaps in the traditional V&V framework being applied currently in industry; (ii) defining and specifying an Enhanced V&V Framework; (iii) based on the justification of the selected modeling, analysis and control tuning techniques on the basis of a well understood interpretation of the peculiarities and criticalities of the selected launcher mission phases and of the specific gaps of the current launcher V&V process; (iv) development, design and implementation of the selected V&V techniques; (v) integration of the developed V&V tools into the proposed enhanced V&V framework; And (vi) Industrialization of the latter through its application to a complex launcher system conducted in an industrial setting and through a comparison of the results with the application of the traditional V&V approach.

This article presents the studies performed by the RFCS consortium related to the first three points above: identification of gaps in the traditional V&V framework (Sections 2 and 3), definition of an enhanced V&V framework based on advanced modeling, analysis and control tuning techniques (Section 4) and justification of the selected advanced techniques in the face of the identified launcher V&V gaps (Section 5).

2. LAUNCHER MISSION PROFILE AND GNC CHALLENGES

This section presents the selected launcher and mission profile for this study, the VEGA launcher vehicle. Also, it discusses the main general GNC challenges in terms of flight control system (FCS) design for the different mission phases. These challenges will serve later to identify the key issues for the current LV V&V.

A. VEGA LAUNCHER SYSTEM AND MISSION

VEGA is the new European Small Launch Vehicle developed under the responsibility of ESA. The prime contractor for the launch vehicle is ELV. The launcher is entering the Qualification phase and the first launch is foreseen at the beginning of 2011 from the Centre Spatial Guyanais in Kourou.

The propulsion system of VEGA is composed of: three solid propellant motors (P80, Zefiro 23 and Zefiro 9) providing thrust for the 1st, 2nd and 3rd stages; and, a bi-propellant liquid engine (LPS) on the 4th stage (AVUM). The LPS can be re-ignited and performs up to 5 boosts. It is used for: transfer orbit injection (1st boost), scattering compensation, final orbit injection (2nd boost) and AVUM de-orbiting (last boost).

All four stages are controlled via a thrust vectoring system (TVC). The 4th stage also includes a Roll and Attitude Control System (RACS). During the propelled phase, the RACS system controls the roll rate while in ballistic phases it performs a three axes control. A strong constraint on the missions is the safety: the separated stages must fall on sea areas.

In the reference mission of VEGA, see Fig. 1, a 1500 Kg payload will be released at 700 Km altitude on a circular Polar Earth Orbit (PEO). In the Qualification flight, a 700 Kg payload will be released at 1450 Km altitude circular orbit of 71 deg inclination. Since the payload (PL) masses range from 300 kg up to 2500 kg, the type of missions are manifold: equatorial, polar, SSO, multi-PL, barbeque mode in long ballistic phase and payload release with spin among others. Along the nominal trajectory, the flight parameters are subject to important - though predictable - variations versus time.

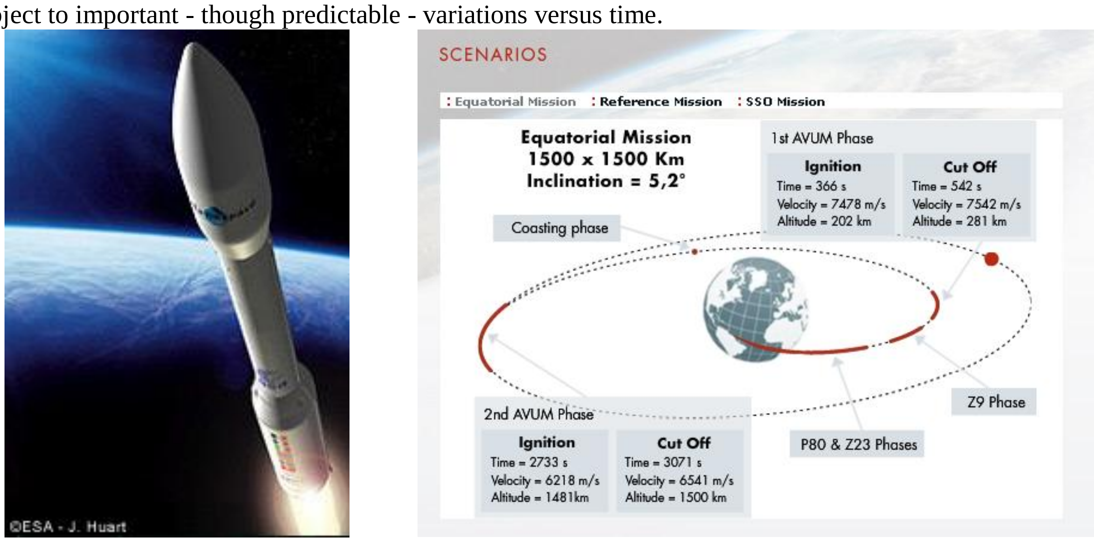

Fig. 1 *VEGA launcher and mission scenarios*

B. LAUNCH VEHICLE FLIGHT CONTROL SYSTEM CHALLENGES

The VEGA launcher is representative of a large set of challenging problems to be dealt with by the FCS that can be presented based on the flight phase.

During the atmospheric flight phase, the challenging problems are:

- Aerodynamic instability of the vehicle,
- Limitation of mechanical loads provoked by wind disturbances (through the angle of attack),
- Minimization of the control demands,
- Coupling of the control with the elastic modes of the launcher,
- High flight parameters variation (dynamic pressure from lift-off to separation; thrust in tail-off).
- Important level of scattering of flight parameters (propulsive, aerodynamic…),
- Coupling between axes due to roll rate and the role of the RACS system.

In the propelled exoatmospheric phase:

- Coupling of the FCS with elastic and sloshing modes of the launcher,
- Stage separation,
- Coupling between axes due to roll rate and the role of the RACS system.

In the ballistic phase:

- Management of the consumption and number of activations of the RACS system,
- Management of the disturbing torques,
- Accuracy of pointing in function of the phases.

In general, the large range of missions and payloads demands of the control laws, for all the flight phases, a high level of robustness and missionization (a given tuning must cover a large range of inertia, elastic frequencies, sloshing modes and of trajectories while minimizing the number of required tunings).

3. CURRENT LAUNCHER V&V APPROACH DESCRIPTION

In this section we summarize the current V&V approach and discuss its general technological gaps.

C. CURRENT LAUNCHER V&V APPROACH

A V&V approach can be defined as the process of ensuring that each step in the process results in the correct product (validation) and that the product being developed satisfies the expected requirements (verification). The first starting point in the any launcher V&V process is the creation of the Avionics Technical Specification, which contains the list of requirements to be fulfilled. Second, Test Plans are defined for all GNC functions in order to assess the performance of the functions and the compliance of the requirements. The test plans describe the validation campaigns (typically incremental from unitary functional testing up to full integrated GNC validation) and their results are reported in Test Reports. The V&V process is iteratively performed and progresses until all the requirements are fulfilled.

The requirements are typically given at two different levels: (i) design, verified by inspection and review, and (ii) performance, expressed generally in a quantitative form (e.g. a variable must be remain inside given bounds) and associated with a probability and a confidence level. This latter type of requirements must be verified numerically through analytical tools and simulations. Additionally, they are to be fulfilled not only on nominal but also on scattered cases defined depending on the system development's phase:

- *Design phase scatterings*: large range to cover evolutions of the program,
- *Production phase scatterings*: reduced range during recurrent production phase. Launcher is frozen and only the remaining dispersions are considered (e.g. on motors)
- *Extended domain non-physical scatterings*: Used to assess the level of robustness

In terms of the validation logics employed, the approaches can be categorized as Worst-Case and Monte Carlo, based on their deterministic or probabilistic nature (and both types are typically applied to frequency and time domain requirements).

The application of the approaches in time-domain is the most straightforward as it consists of running a (more or less high-fidelity) nonlinear simulator of the launcher over any of the relevant flight phases or for the full mission. These approaches also have the advantage of allowing testing for all the known nonlinearities and mode changes. In contrasts, the application of the approaches to the frequency domain approach can only be performed currently by using LTI models. This is conservative since a flight is in general not stationary and thus, the approaches must use a frozen-time analysis framework. Nevertheless, although constrained by these assumptions, the frequency domain is useful as it gives information that the time domain cannot provide. For instance, unless they are close to instability, the elastic modes are hardly visible in time domain simulations.

The worst-case / vertex approach

This type of (deterministic) validation approach consists of checking the GNC behaviour on a set of selected configurations. For example, with the parameters set at the limits of the intervals (maximal or minimal) at especially relevant flight instances (lift-off, stage separation…).

For instance a TVC control tuning could be assessed on the so-called low frequency (LF) and high frequency (HF). The first corresponds to those cases with maximal dynamic pressure and minimal thrust, while the second to those with minimal dynamic pressure and maximal thrust. The names LF and HF refer to the fact that these worst-cases respectively impact the LF gain margin and the HF gain margin. This knowledge results from experience and from physical insight into the equations of the simplified system.

It can be argued that this type of approach should be called "vertex cases" because from all the combinations, all the configurations are not worst (for example minimal dynamic pressure and minimal thrust). The advantages are that the method provides for a simple and rapid verification of the requirements, and the drawbacks are that it may be too sizing and that there is no guarantee in obtaining the worst case.

The Monte-Carlo approach

It consists of randomly sampling the parameters according to statistical distributions and to deduce the values of criteria involved in the requirements. The number of simulations depends on the specified requirements probability and confidence levels: for example, for launcher consumption is required at least 1000 runs (99.9% probability at 60% of confidence) while for control accuracy is sufficient with 100 runs (99% probability and 60% confidence).

It may happen that the dependence of the criteria versus the parameters is not simple or monotonous. In this case, the statistical approach allows exploring the domain of variations. Additionally, when the requirements are specified with a level of probability and confidence, their fulfillment must be assessed in terms of probability analysis and this approach is the most natural.

The method is simple to implement and useful for mean / variance analysis. The drawbacks are that it is computationally heavy and questionable for maximum/minimum values analysis.

D. OVERALL TECHNOLOGY GAPS IN THE CURRENT LV V&V APPROACH

Based on the approach presented above and the VEGA GNC design and qualification experience, the following bullets present the identified main overall gaps in the current LV V&V approach. They have been organized into three main themes:

Completeness of the coverage of configurations

Currently there is a lack of confidence that the analyzed configurations are sufficient to cover:

- All the flight instants: currently a sampling of 1 sec for the VEGA flight phase P80 is used to assess stability margins using the frozen parameters approach.
- The entire payload mass range: currently the tests focus on a set of predefined PL (two dozens) and are often limited to the range limits –and assuming monotonous behavior of the criteria. This assumption is based on physical and mathematical proofs but is limited to simplified models.
- All the missions: in the current logic, an envelope of trajectory parameters is considered assuming that it covers all the possible missions. This approach should be made more explicit to master clearly the frontier of the flight domains.
- Scattering domain: the Worst-Case or Vertex approach are not sufficient if the dependence between criteria and parameters is non linear. The Monte-Carlo approach may be not sufficient if the number of runs is limited.

Consistent verification of the different requirements

The probability and confidence levels of the different requirements are also different but all must be verified together in the same set of simulations.

The current approach is to select the number of runs as the maximum number of runs compatible with the requirement with the lowest probability. At the same time, several requirements (the less stringent ones) are tested using the Worst-Case approach since this is sufficient. An improvement would be to manage this process systematically.

Additionally, trade-off curves mapping conflicting performance objectives and providing information on the limitations and axis of design/system improvement are not easily obtained with the current worst-case and Monte Carlo simulation approaches.

Precise assessment of the margins

The current approach does not always provide a clear vision of the margins. The results are often more conservative than necessary. This is due to the use of simplified (for tractability purposes) models in the assessment:

- In flight phases with high parametric variations (tail off of the solid rocket motors; around maximal dynamic pressure), the stability margins are assessed in the frame of LTI systems. But it is noted that possibly this analysis could result in overtly negative results (transient instability in the LTI definition sense) while the launcher be perfectly stable in the nonlinear simulation.
- Similarly, the calculation of margins in a LTI frozen-time setting could yield overtly positive results declaring sufficient margins in the LTI framework but too reduced, or even unstable, practical margins in the full nonlinear setting due to time-varying or nonlinear effects.
- The parameters are often considered independent. The uncertain domain can be represented as a hypercube in n dimensions. In practice, the parameters are not independent and the actual uncertain domain is a volume included in the hypercube.

In addition, and in particular for time domain simulations, the results obtained do not give a clear distance to the bounds. It is always useful to know for which level of scattering the requirements are violated. This could be done by computing a kind of partial derivatives of the requirements with respect to the launcher parameters. This precious knowledge could help the designer to better manage the trade-off at system level.

4. ENHANCED FRAMEWORK FOR LAUNCHER GNC DESIGN V&V

In this section the general definition of a GNC design V&V framework is outlined, followed by a brief presentation of the advanced analysis techniques that are being considered within the RFCS project and concluding with the presentation of the enhanced launcher V&V

Any GNC design process and its associated V&V activities must always be supported by a GNC design V&V framework. By framework it is understood the methodological application of the following five elements:

- **Engineering activities**: understood as the set of activities to be performed during the V&V process.
- **Problem definition and objectives**: refers to the rigorous establishment and formalization of the verification problem (scope, models, V&V objectives and underlying constraints and hypotheses).
- **System property set and associated metrics**: the objective is to define exactly how to measure, during the verification, the performance of the GNC. This is done by establishing a V&V matrix that provides metrics to assess the achievement of established system properties, defined as follows:

  System property: properties of the GNC system that should be established by design and afterwards verified and validated accordingly. Usually they are organized around classical control performance concepts: from nominal stability (NS) to robust performance (RP).

  Performance metrics: understood as ways to measure and evaluate the System properties, as for example roll rate and angular limits, fault thresholds, etc.
- **Analysis V&V techniques** to establish the desired system properties, understood as the combination of mathematical formulation (of the way system properties are guaranteed by means of a computable condition) with underlying analysis tools (analytical, simulation-based or a mixed of both).
- **Software tools for analysis**: these are the numerical implementation of the analysis results by which the desired system property can be checked.

E. ADVANCED ANALYSIS V&V TECHNIQUES

The analysis V&V techniques can be classified as: analytical or simulation-based methods.

Analytical V&V techniques

Modern analytical analysis techniques depend on the representation of the system in linear fractional transformation (LFT) form. Without delving on the different approaches used to generate an LFT model, it is highlighted that there are three broad types of LFT models [9, 10]:

- LTI-LFT: captures real parametric uncertainty (e.g. mass, payload…)
- LPV-LFT: captures time-varying parameter dependence (e.g. Mach)
- NL-LFT: captures nonlinear effects (e.g. saturations, dead-zones…)

The analytical V&V techniques are characterized by their reliance on algebraic, closed-form or linear relationships to characterize a property of the system, typically connected to stability and performance. Their character is mostly local although some recent analytical techniques have advanced the state-of-the-art sufficiently to consider them as global (although their supporting tools are not at a mature state to be applicable except to the lowest dimension and simplest-dynamics systems).

A classification of these approaches in term of the model format they require is as follows:

- *Linear*: applicable to linear time invariant (LTI) systems in linear fractional transformation (LFT) form. These approaches are the most widespread and used but tend to be conservative.
- *Nonlinear*: applicable to nonlinear systems (including linear systems in LFT form containing nonlinearities). The nonlinear analytical techniques are founded in the theory of Lyapunov but except for specific nonlinear system representations are quite challenging to apply.
- *Hybrid*: applicable to the class of real systems which contain discrete and continuous time dynamics. These techniques are of recent appearance and even though they are mostly applicable to small-dimension systems are a step in developing global analytical analysis.

Table 1 comparatively summarizes the main advantages, drawbacks and standard metrics for the most known analytical V&V techniques.

Table 1 *Comparative assessment of analytical analysis V&V approaches*

Approach		Advantages	Drawbacks
LINEAR	**Small-Gain Theorem**	Systems in LFT form Uncertainty operator can be time-varying or nonlinear Widespread and reliable tools	Conservative
	Structured Singular Value	Systems in LFT form Less conservative than above Widespread and reliable tools	NP-hard calculation for exact value (but in practice good upper and lower bounds)
NONLINEAR	**Lyapunov theory**	The basis for all nonlinear analyses	Difficult to search for candidate solutions
	Integral Quadratic Constraints	LFT systems with nonlinear or time-varying terms Convex optimization Unified framework for analysis	Certain computational complexity
HYBRID	**Sum of Squares**	Convex optimization Hybrid systems	Only systems in polynomial form Computational high for complex systems
	Barrier Functions	Convex for systems in polynomial format Hybrid systems	Non-convex in general case
	Reachable Sets / Viability Theory	Switched/hybrid system application Nonlinear systems and global analyses	Very limited due to computational tools

Simulation-based V&V techniques

Simulation-based algorithms can be used to address the two main V&V purposes:

Control Clearance: to provide a degree of confidence that a controller satisfies a given property with a given probability.

Worst-Case Identification: to find the worst-case(s) with respect to all admissible parameter combinations.

Simulation-based methods can handle any analysis criteria expressible in mathematical form and can be used with any kind of simulation model, no matter how complex. However, the reliability and efficiency of the approach strongly depends on a number of factors, principally: choice of cost-function, choice of optimization algorithm, and choice of tuning parameters. Furthermore, the performance of a given optimization algorithm is generally problem dependent, and there is no unique optimization algorithm for general classes of problems which will guarantee computation of the true global solution with reasonable computational complexity [3, 12, 13, 14].

Table 2 shows a comparative of computational V&V techniques. They are classified into four main classes of optimization algorithms:

- *Local optimization methods*: which use evaluation of the cost function gradient to increase convergence but might suffer from less reliable execution in more realistic cases where numerical approximations of the gradient are required.
- *Global probabilistic optimization methods*: these methods perform statistical modeling based on random samples to describe the system behaviour. They are computationally very intensive, and the most well known is the industrial standard V&V approach of Monte Carlo.
- *Global deterministic optimization methods*: these methods represent an alternative to the statistical methods above. The idea behind these global methods is to substitute the random search performed in the previous methods by deterministic searches.
- *Mixed optimization methods*: for this class no method in particular is presented in Table 2 since they typically arise from a combination of some of the previous global and local methods.

Table 2 *Comparative assessment of simulation-based analysis V&V approaches*

Approach		Advantages	Drawbacks
LOCAL	**Sequential Quadratic Programming**	Typically low number of evaluations and iterations Very reliable implementation	Local Low reliability and noisy for complex problems
	Bounded Quasi Newton	Applicable to large scale problems Handles nonlinear programs with simple bounds Super-linear convergence	Local Poor convergence for poor numerical approximations of the gradients
	Pattern Search	Numerically more robust than above methods Gradient-free (only uses criteria evaluation)	Local Slower convergence than above methods
GLOBAL PROBABILISTIC	**Monte Carlo**	Standard in industry for V&V	Computationally very expensive
	Las Vegas	Guaranteed solution Global probabilistic	Random running time Immature in control field
	Importance Sampling	Increase precision of MC methods Exploits critical regions' knowledge Global probabilistic	Choice of biased distribution is key element Requires very good knowledge on system
	Genetic Algorithms	Popular & robust method for *optimal* solution Global probabilistic	Computationally expensive No convergence proofs
	Evolutionary Strategies	Popular & robust method for *suboptimal* solution Candidate solutions are real-valued Global probabilistic	Computationally expensive No convergence proofs
	Differential Evolution	Simplicity Better performance than previous Global probabilistic	Not very mature No convergence proofs Computationally expensive
GLOBAL DETERMINISTIC	**Dividing Rectangles**	Global deterministic & does not need gradient Naturally parallelization algorithm Converge to solution if run for long time	Only asymptotic proof Difficult to mix with local approaches Long convergence if solution is on vertices
	Quasi-Monte Carlo	Global deterministic & does not need gradient Can improve performance of standard MC	Nontrivial to use depending on problem Convergence is not assured
	Polynomial Chaos	Uncertainty propagation method Global deterministic Computationally efficient	Very recent, Tools not readily available Selection of basis functions describing random parameters

F. DEFINITION OF AN ENHANCED V&V FRAMEWORK FOR LAUNCHER V&V

The aim of the enhanced design V&V Framework is to reduce significantly the effort required to obtained a verified control law design by introducing the latest (matured) advances in robust multivariable control technology. The framework should represent an incremental step from the traditional approach in order to ensure its acceptability and applicability, and should consider all the control cycle phases: from modeling to design and analysis.

The proposed framework is conceptualized around a set of software tools developed by Consortium partners that cover each of the phases in the design V&V cycle. This allows precisely to provide an incremental approach (from the traditional V&V) while ensuring that the resulting tool is mature and ready to use. Fig. 2 shows the framework schematic concept, including the techniques used (classified into traditional and advanced, and as analytical analysis tools (AAT) and simulation analysis tools (SAT):

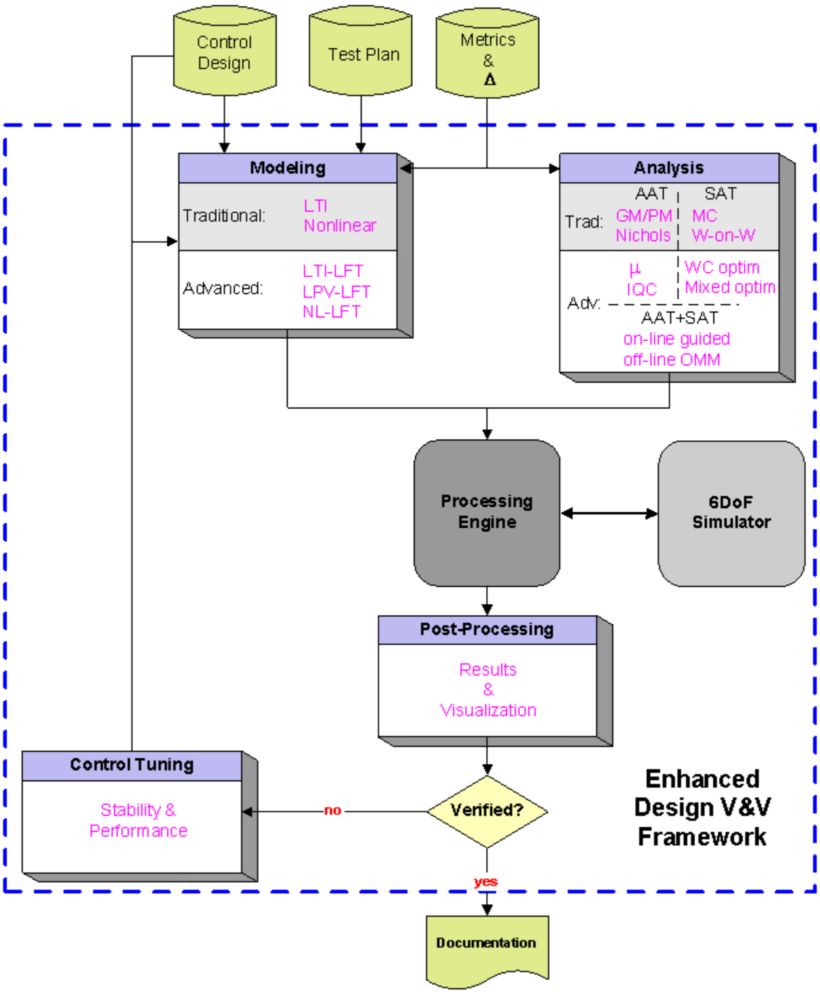

Fig. 2 *Enhanced Design V&V Framework Concept*

The inputs and outputs to the framework are:

- *Control design*: this is the designed control law to be V&V. It can be given in any form but for control tuning must be adapted into a parameterized model.
- *Test plan*: it refers to the V&V test plan information, including test cases and conditions.
- *Metrics and Uncertainty Set*: depending on the task at hand the user may modify, or select from a set, the corresponding V&V metric and channels to observe. The user must define also the uncertainty set, including parameters, ranges and distributions.
- *V&V report*: automatically generated contains all the appropriate information from the process: simulation settings, selected metrics and algorithms, post-processing results.

The main components in the framework are:

- ☐ ***Modeling***: this component includes traditional and advanced modeling techniques such as:
  - *Traditional techniques*: trimming and linearization (at defined points along the trajectory)
  - *Advanced techniques*: LFT models based on parametric uncertainty as well as linear parameter varying models (LPV-LFT) capturing the dynamic variation, and nonlinear LFT models (NL-LFT) capturing nonlinearities such as magnitude/rate saturations or time delays.
- ☐ ***Analysis***: as in the modeling component we find traditional and advanced tools:
  - *Traditional techniques*

    AAT: includes standard linear analysis such as gain/phase margins and Nichols plots.

    SAT: includes Monte Carlo, vertex and worst-on-worst nonlinear time-domain simulations.
  - *Advanced techniques*

    AAT: all modern robust multivariable approaches from Table 1 fit in here, but mainly we will focus on:

    - ➢ *Structured Singular Value*, μ: Applicable to linear systems in LFT form for analysis of real and complex uncertainty effects.
    - ➢ *Integral Quadratic Constraints*, IQC: As above plus also applicable to nonlinear systems in LFT form for analysis of nonlinear and time-varying effects.

    Note that compared to the traditional AAT techniques used in the traditional V&V framework, the selected advanced techniques will allow performing robust stability (RS) and robust performance (RP) analysis for: complex uncertainty (e.g. flexible or unmodeled dynamics), real uncertainty (e.g. mass or moments of inertia), time-varying parameters (e.g. Mach or dynamic pressure) and a large plethora of nonlinearities (e.g. time-delays or saturations).

    SAT: as shown in Table 2 there is a wide range of algorithms, from local deterministic to global probabilistic and including mixed (local and global).

    - ➢ *Local or Global methods*: The application of the methods in Table 2 that are available to the consortium [12, 13, 14, 15, 16] will bring the following benefits with respect to the traditional V&V framework:
      - The use of multi-objective analysis criteria and optimization algorithms allows the designers to map conflicting worst-case performance objectives onto the uncertain parameter space, yielding knowledge on the trade-offs and limitations for the Launcher V&V.
      - The availability of multiple optimization algorithms, all applied to the same Launcher V&V problem, will allow harnessing knowledge on algorithm computational performance in this specific problem while serving as independent verification of the resulting results.
    - ➢ *Mixed (local & global) optimization:* Local optimization approaches have high chances of getting locked into a local optimum, particularly when there is little information available from which to choose a good initial starting point. However, if the initial guess is close to the true worst-case, local optimization methods can converge to the global optimum extremely quickly. Global optimization methods, on the other hand, have a high probability of converging to the global solution if allowed to run for a long enough time and with reasonably correct probabilities. Nevertheless, their rate of convergence can be very slow, and moreover, there is still no guarantee of convergence to the true global solution. In the last 15 year, mixing of local/global methods have been performed with considerably success in reducing the number of iterations required to find the worst-case or perform the control clearance in several fields [15, 16, 17, 18].

      Compared to the classical worst-case approach, whereby robustness is assessed randomly on a very large parameter space or by using maximum/minimum combinations, the advantages are:

- The tremendous costs involved when simultaneously checking the robustness for many uncertain parameters is greatly reduced. This occurs because the number of function evaluations necessary to compute the worst-case parameter combination (or clear the controller) is usually much lower than that corresponding to evaluating the function in a brute Monte Carlo fashion.
- By allowing in the optimization-approach to continuously vary the parameters within the given parameter space, better coverage of the space is obtained and thus the results are more reliable. In the classical approach there is no guarantee that the troublesome conditions have been cleared. Thus, if the minimum occurs at a point which was not selected for testing, then the clearance results could be false.

AAT+SAT: this refers to the integration of AAT and SAT tools. This class of techniques attempts to reconcile the individual advantages of each technique while compensating for their individual limitations. Two main classes of approaches are considered:

- *Offline Guided Optimization*: The goal of this integrated approach [5, 19] is to combine the advantages of linear worst-case analysis techniques such as the structured singular value and linear fractional transformation (i.e. their analytical nature, easily verifiable implementations, results validation, reduced computational expense) with the advantages of simulation-based analysis algorithms (i.e. nonlinear considerations and certifiable probabilities) while avoiding, or ameliorating, their main drawbacks: linear character and computation expense respectively.
- *Online Margin Meter (OMM)*: A step further in the AAT+SAT integration process is to use online flight data in which margins are part of the telemetry message and represent part of the launcher's health monitoring. The OMM approach uses also μ and LFT models together online flight data (in our case, online simulation data) to give a scalar value quantifying the distance of the vehicle to the required margins. This type of tool has already been considered in [20] in the context of online monitoring of the flutter margin of an aircraft during flight tests and will be now demonstrated for launchers V&V.

☐ ***Control tuning***: this component allows closing the loop between V&V and design. Together with the advanced analysis techniques from the previous component, it allows the engineer to effectively use those results to re-design the controller so that a positive V&V outcome is obtained in a minimum time and effort.

Control tuning must be considered as an optimization of a controller's parameters in the face of (multi) design objectives and criteria. This is precisely the definition of DLR's multi-objective parameter synthesis (MOPS) [12, 13, 14], which uses multi-objective synthesis and clearance algorithms in a min-max parameter optimization framework.

The MOPS software tool requires only that the models (of plant and controller) are parameterized, and it is highlighted that LFT modeling techniques are actually applicable to any parameterized system. Thus, an additional advantage of using MOPS and LFT representations is that the models used for analysis and control retuning are the same, or arise from the same higher-fidelity LFT model. This is important as it provides the GNC engineer with a methodology that unifies the modeling requirements for each technique while allowing for easy modification and tracing of the LFT models.

5. ADVANTAGES FROM MODERN ANALYSIS TECHNIQUES FOR LAUNCHER V&V

In this section the technological gaps specifically found in launcher V&V are identified (based on the current launcher V&V description and general gap analysis of Section 3) and the advantages associated to the application of the advanced techniques that compose the enhanced V&V framework (Section 4) discussed. The structure for each identified gap is to describe the problem, present the current approach, summarize the identified technological gap (i.e. the limitations of the traditional V&V approach) and identify and discuss the advantages offered by using the most appropriate advanced technique.

Coupling TVC control / Roll control

In presence of roll, the launcher's pitch and yaw axes become coupled. If the roll is not controlled to zero but only constrained to remain below a limit value (which is less demanding for a dedicated roll control system), the question is then how to analyze the effect of this coupling on the stability margins of the control law.

The traditional approach is to use single-input-single-output (SISO) stability margins and perform verification via Monte-Carlo or worst-case simulations.

The current approach represents a technological gap since the coupling of the pitch and yaw motions results in a multi-input-multi-output (MIMO) system and the obtained SISO margins are thus conservative. A technological improvement will be to rigorously address the MIMO stability margins [7] and to generalize the approach to cases where, for example, roll rate is not anymore a known constant value but it is contained within a given interval. Additionally, guaranteed proofs on the maximum roll rate allowed and associated performance degradation curves will enable the system engineer to decide on the most convenient roll-control approach. Both AAT techniques considered, μ and IQC, allow considering MIMO systems with real parametric variations but only the IQC techniques can account for time-varying parameters, which might be more appropriate. Both can be used also to get worst-case values of the roll-rate represented as performance degradations curves [21, 22].

Robustness of control versus payload modes and trajectories

The V&V problem is to assure that the control is robust for different types of payloads (real parametric variations) and for an envelope of potential trajectories (real time-varying parameters).

The current approach relies on the frequency validation of the control on each channel (SISO approach) via Nichols plots from which the margins are deduced (LF rigid gain, rigid phase, HF rigid gain, 1st mode phase, upper modes' gains). The Nichols plots are computed on a set of predefined worst-cases (or rather "vertex cases" as mentioned before).

Two technology gaps are identified:

- Current analyses arise from combinations in a parameter set, with only minimal and maximal values, selected from engineering know-how. It is necessary to ensure that the margins are obtained on a whole domain of data for: (i) the range of PL masses (and introducing a dependence of inertial and elastic data versus the PL mass), (ii) time intervals (guaranteed for all instants and not only a sample subset), and (iii) the entire scattering domain (and not only at the vertices since for non linear dependences worst margins can be reached inside the domain).
- Reduction of the current analysis' conservativeness by introducing correlations between parameters (as already introduced for dynamic pressure and thrust). For example, the parameters could be expressed in terms of a specific parameter retained for scheduling (velocity for instance).

From a pure analytical perspective (i.e. quantitative guaranteed proofs), both of the advanced AAT techniques discussed before address the two technological gaps –in unison with the use of LFT models capturing the variations and/or the parameters correlations. Further, the simulation-based techniques proposed above can also be used, in a nonlinear time-domain setting, to obtain worst-case or clear the controller in the flight envelope without resorting to limited (vertex) or highly intensive (Monte Carlo) approaches.

Stability of rapid time varying dynamics

The V&V problem is the presence of tail-off phases. These phases are common in solid rocket motors, which cannot be cut off and thus the launcher must wait for the end of the combustion. This means that in a short period of time (10 to 20 seconds), the thrust decreases from its steady level down to zero. In addition in some flight phases, the dynamic pressure decreases a lot due to the exponential diminution of air density. These effects result in a highly non-stationary system in which parameters' variations are of the same order of magnitude as some variables.

The current verification approach is based on frozen time Nichols (for LTI models) and in time-domain Monte-Carlo simulations.

Unfortunately, the use of frozen-time LTI stability analysis tools for non-stationary system does not provide adequate assurance of the results and results in a high level of conservativeness. This technological gap could be filled by deriving stability margins accounting for the time varying dynamics as done by the IQC technique [8].

Linear and nonlinear stability of TVC control in presence of elastic and sloshing modes

The TVC control is designed for the rigid mode i.e. rotation around the center of mass of the launcher, which is unstable in the atmospheric phase while in the exoatmospheric phase is a double integrator. Additionally, in presence of modes (elastic or sloshing), the launcher may lose stability thus attention is to be paid to provide these modes with sufficient margins.

The current approach is reflected in technical specification and the analysis performed via linear techniques assuming simplified models (rigid or first-order approximations of the elastic/sloshing modes).

A technological gap arises from those situations not covered by the current linear approach, such as:

- A sloshing mode can be unstable by looking at Nichols plot while not presenting any risk in the time scale of a flight phase because it is very slow and/or involve low energy.
- An elastic mode can be excited by nonlinearities (backlash or hysteresis) of an actuator but it is not visible by looking at a Nichols plot.

The above two technological gaps are now only addressed in time domain (with the usual limitations in coverage and computational expense). But as in the first three problems, the μ and IQC analysis tools can be used to address the first gap and the IQC also for the latter.

Stability & performances of RACS Control

The RACS control of a launcher vehicle is an on-off modulation system where the application of classical analysis techniques is not straightforward as most cannot address discrete systems.

Currently, the RACS control is checked only via a campaign of time-domain simulations used to check: stability, axes coupling good behaviour, consumption, number of activation and absence of higher dynamic modes' coupling.

Unfortunately, time-domain simulations provide only a limited analysis capability for the above issues. Thus, it would be desirable to be able to foresee nonlinear effects in advance, such as the existence of limit cycles and predict stability as well as number of activations from an analytical quantitative perspective. IQC techniques are highly appropriate for the task as well as other analytical techniques, i.e. describing functions with μ [23].

Assessment of Loads Constraints

The verification of general loads on the launcher is of high concern. This criterion is typically expressed in the time-domain (as a maximal value of the product dynamic pressure by angle of attack computed over time) and cannot be foreseen during design in the frequency domain.

The current verification is thus performed via time-domain simulations with each launcher parameter scattered depending on the model (uniform, Gaussian, mixed), and the simulations performed under different configurations:

- Worst case approach: a sizing wind profile with a gust occurring at various altitude, is applied during the atmospheric phase,
- Monte Carlo approach: uses a set of statistical winds (picked from a database of real wind measurements).

It is envisioned that in order to avoid the use of intensive Monte Carlo simulations in which the designer is only interested in computing a maximal level, an approach based on optimization could be applied to verify the load constraints. For example, the simulation-based algorithms could be used applying a cost function based on a profile versus Mach not to be exceeded. For each Mach number, the result would be a set of scattering on parameters leading to reach the limit. There is not necessarily one solution to the problem which is why it would be useful to give the limiting domain of parameters. MOPS [12, 13, 14] and other simulation-based algorithms [15, 16] can be exploited here since for example MOPS can perform, produce and visualize this type of trade-off and performance degradation plots for multi-criteria and nonlinear simulation-based analysis. For example, Fig. 3 shows the visualization capabilities of MOPS for the statistical indicators and criteria optimization progress of the automatic landing design problem [24] (left plot) and for assessing the gust load alleviation improvements of a design based on physically-meaningful objective functions [25] (right plot).

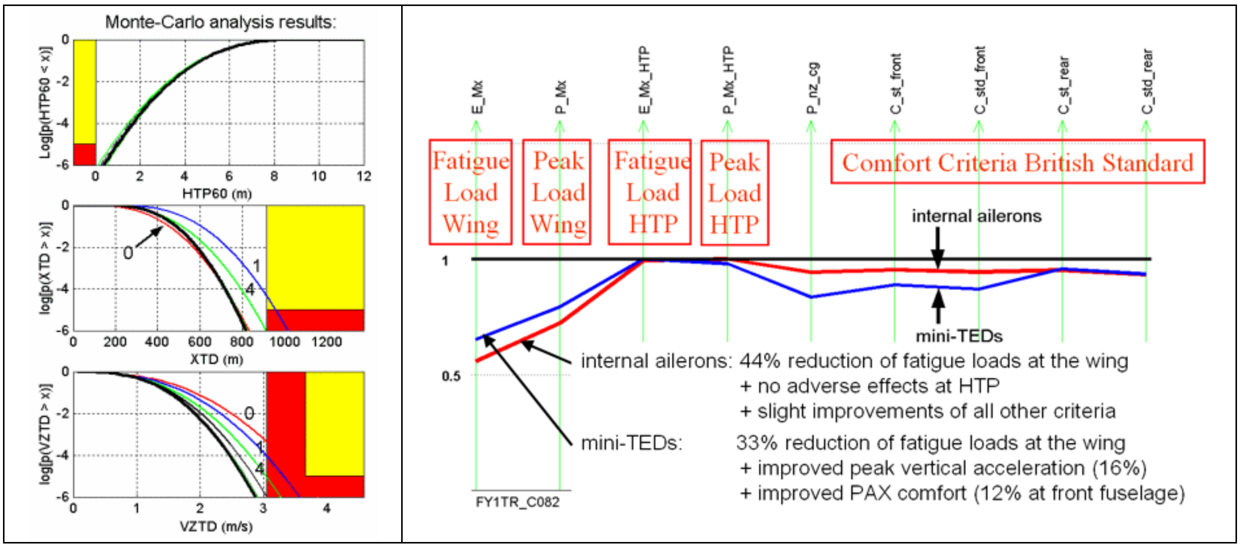

Fig. 3 *Visualization of Monte-Carlo criteria optimization for automatic landing controller (left) [24] and of optimization criteria for gust load alleviation and comfort improvement design (right) [25].*

Coverage of performance of PL release

Finally, it is noted that the payload release is composed of a set of maneuvers (slew, spin if needed, release, de-spin, CCAM) with different requirements and tunings for each of flight phase. Similarly, the requirements and associated tunings must be checked for a wide set of configurations in order to ensure their performance and robustness (various PL masses, various scenarios: spin or not spin…)

The most straightforward mode of verification is again through Monte-Carlo simulations for a given set of payload masses and scenarios, but then again this represents a very intensive simulation campaign (required to be repeated every time a change in the GNC occurs during the program evolution).

A technological gap is then to assure that the payload release performance assessment covers the entire domain, and that the compliance of the tuning (stability, number of activations and consumption…) is demonstrated without the need to recourse to the intensive nonlinear time-domain simulation campaigns. In order to address this the worst-case and control clearance optimization algorithms can be used but also the integrated (AAT+SAT) approaches could be used to provide an analytical guarantee demonstrating the compliance of the tuning (stability, number of activations and consumption…).

6. CONCLUSION

This article has presented a detailed assessment of the current launcher V&V practices and their shortcomings and difficulties as well as presenting an enhanced V&V framework based on the use of advanced modeling, analysis and control tuning techniques. Using the VEGA launcher as the specific launcher case, the most common and relevant technology gaps in the traditional launcher V&V framework were identified and potential solutions presented based on the use of modern techniques.

REFERENCES

[1] Mauffrey, S., Meunier, P., Pignie, G., Biard, A., Ganet, M., Rongier, I. "H∞ control for the ARIANE 5 PLUS launcher: The industrialisation of a new technology," 5-th International Conference on Launcher Technology, Madrid, Spain, 2003.

[2] Morita, Y., "A Success in Robust Control Design for a Satellite Launcher," Proceeding on the 26-th IASTED International Conference Modelling, Identification, and Control - Insbruck, 2007.

[3] Fielding et al., *Advanced Techniques for Clearance of Flight Control Laws*, Lecture Notes in Control and Information Science. Berlin: Springer-Verlag, 2002.

[4] Jacklin, S.A., Schumann, J.M., Gupta, P.P., Richard, R., Guenther, K., and Soares, F., "Development of Advanced Verification and Validation Procedures and Tools for the Certification of Learning Systems in Aerospace Applications," Proceedings of Infotech aerospace Conference, Arlington, VA, Sept. 26-29, 2005.

[5] Belcastro, C. and Belcastro, C., “On the Validation of Safety Critical Aircraft Systems, Part II: An Overview of Analytic and Simulation Methods,” AIAA Guidance, Navigation and Control Conference, AIAA-2003-5560, August 2003.

[6] Hanson J., “Learning About Ares I from Monte Carlo Simulation,” AIAA Guidance, Navigation and Control Conference and Exhibit, Honolulu, Hawaii, Aug. 18-21, 2008

[7] Roux, C., Cruciani, I., “Roll Coupling Effects on the Stability Margins for VEGA Launcher”, AIAA GNC 2007.

[8] Roux, C., Cruciani, I., “Scheduling Schemes and Control Law Robustness in atmospheric flight of VEGA”, ESA-GNC Tralee 2008

[9] Marcos, A., Bates, D.G., Postlethwaite, I. *Nonlinear LFT modeling for on-ground transport aircraft, Chapter 5, Nonlinear Analysis and Synthesis Techniques for Aircraft Control*, Series: Lecture Notes in Control and Information Sciences, Vol. 365 Bates, Declan; Hagström, Martin (Eds.)

[10] Marcos, A., De Zaiacomo, G., Mostaza, D., Kerr, M., Veenman, J., Scherer, C., Bennani, S., “Application to a re-entry vehicle of LPV/IQC modeling, design and analysis methods”, submitted to the AIAA GNC 2010.

[11] Rotunno, M., Fiorenzani, T., Petritoli, P., Bennani, S., “Modern Analysis Techniques for Gain Scheduled Thrust Vector Controller of Launchers,” Joint CCA, CACSD, and ISIC, 2006.

[12] Joos, H.-D., Bals, J., Looye, G., Schnepper, K., and Varga, A., “A multi-objective optimisation-based software environment for control systems design,” IEEE International Symposium on Computer Aided Control System Design, Glasgow, Scotland, U.K., September 2002, pp. 7-14.

[13] Joos, H.-D., MOPS - Multi-Objective Parameter Synthesis; User's Guide V5.3, DLR-IB, 515-08-37, 2008.

[14] Joos, H.-D., “Flight control law clearance using optimization-based worst-case search,” 6th IFAC Symposium on Robust Control Design, Haifa, Israel, 2009.

[15] P.P. Menon, D. G. Bates, and I. Postlethwaite, “Nonlinear robustness analysis of flight control laws for highly augmented aircraft,” IFAC Control Engineering Practice, Vol. 15, pp. 655–662,2007.

[16] P.P. Menon, A. Marcos, I. Postlethwaite, S. Bennani, D.G. Bates, “Multi-Objective Worst-Case Analysis of Flight Control Laws for Re-Entry Vehicles,” IFAC World Congress on Automatic Control, Korea, 2008

[17] J. Yen, J. C. Liao, D. Randolph, and B. Lee, “A hybrid approach to modeling metabolic systems using genetic algorithm and simplex method”, 11th IEEE Conference on Artificial Intelligence for Applications, pp. 277–283, Los Angeles, CA, Feburary 1995.

[18] F. G. Lobo and D. E. Goldberg, Decision making in a hybrid genetic algorithm, IlliGAL Report No. 96009, September 1996.

[19] Bateman, A., D. Ward, and G. Balas, “Robust/Worst-Case Analysis and Simulation Tools,” AIAA Guidance, Navigation, and Control Conf., San Francisco, CA, August 15-18, 2005.

[20] R. Lind, M. Brenner, “Flutterometer: An On-Line Tool to Predict Robust Flutter Margins”, J. of Aircraft, Vol.37 No.6, 2000

[21] G.J. Balas, J.C. Doyle, K. Glover, A.K. Packard, and R. Smith, .The m Analysis and Synthesis Toolbox,. MUSYN and The Mathworks, 1996, Natick, MA.

[22] Balas, G., Chiang, R., Packard, A., Safonov, M. ”Robust Control Toolbox v3.0”, The Mathwoks, 2006

[23] Ferreres, G. and V. Fromion. “Nonlinearanalysis in the presence of parametric uncertainty,” International Journal of Control, 69, 695-716, 1998.

[24] Looye, G., Joos, H.-D.,” Design of Robust Dynamic Inversion Control Laws using Multi-objective Optimization,” AIAA Guidance Navigation, and Control Conference, Montreal, 2001.

[25] Hecker, S., Hahn, K.-U., "Advanced Gust Load Alleviation System for large flexible Aircraft", 1st CEAS European Air and Space Conference, Berlin, Germany, September 2007