Stability analysis using a coupled model of TVC actuator control loop and structural dynamics of a Launch Vehicle

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Abstract

LaSer is a CNES tool initially aimed at analyzing Launch Vehicles low frequency dynamic environment. It couples a Launch Vehicle FEM and a TVC actuators model. It has been validated w.r.t. hardware tests. Tool has been derived to allow stability and performances analyses of small loop control. Methodology has been applied to P80 Solid Rocket Motor as first stage of a typical Launch Vehicle. Results in nominal and scattered cases have shown efficiency of the methodology. They also have increased confidence in the robustness of P80 small loop control, demonstrating significant margins despite presence of bending modes and actuators non-linearties.

1. Introduction

A 80-ton-loaded solid rocket motor, called P80, has been developed by EUROPROPULSION as Prime contractor, under the responsibility of CNES Launchers Directorate. Its qualification review has been successfully held in 2010.

Not only designed as the first stage for a Launch Vehicle, it has been developed as a demonstrator for a future evolution of ARIANE 5 booster. As such it implements several technological breakthroughs [1]: one of them is the use of high power Electro-Mechanical Actuators (EMA), associated to low torque motor nozzle flexible joint, to allow Thrust Vector Control (TVC).

P80 so-called *TVC small loop control* has been classified as a critical function, due to:

- requested high performances and robustness for the Launch Vehicle control during atmospheric phase flight;
- complex interactions with Launch Vehicle dynamics.

Criticality of coupling with Launch Vehicle bending modes is detailed in [2]: it leads to a potential reduction of small loop stability margins and justifies the development of dedicated methods and tools to assess the robustness of a small loop controller w.r.t. such phenomena.

To better characterize the interactions existing between TVC small loop control and Launch Vehicle's slender body dynamics, CNES has developed a dedicated software. LaSer tool is initially aimed at analyzing low frequency dynamics at various Launch Vehicle locations, when this latter is submitted to exciting loads (wind gust, deflection spikes, etc.). It couples a Launch Vehicle dynamic model, a simplified Payload model, and a small loop actuators model. This latter has been developed by EUROPROPULSION and its subcontractor SABCA, and validated using of H/W qualification tests results. It is representative of actuators dynamic behaviour, and in particular of its non-linearities.

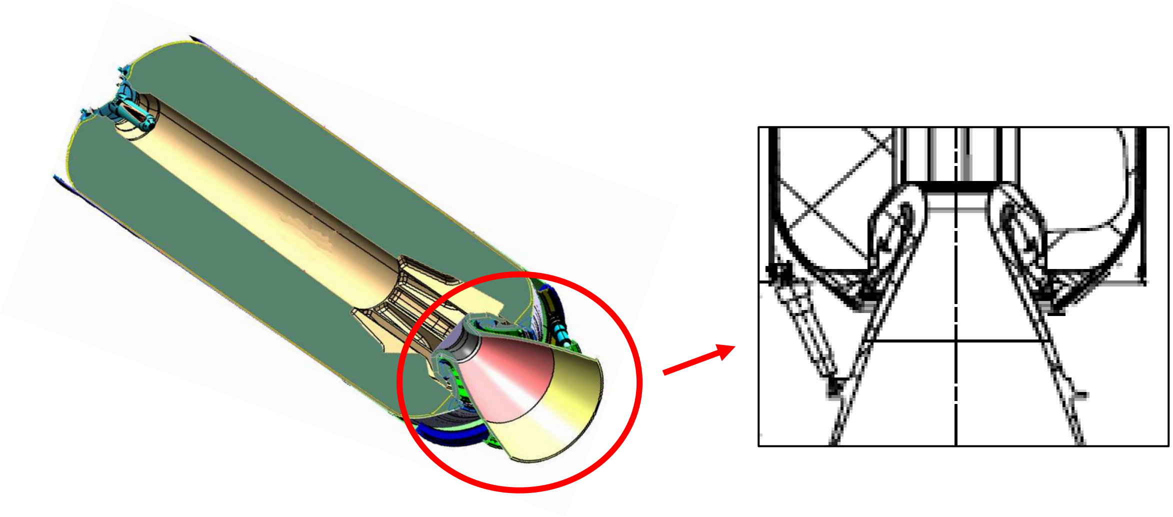

Figure 1.1: P80 Thrust Vector Control lay-out

LaSer tool general features are first presented in § 2. Its dynamics prediction capacity is demonstrated using P80 firing test results.

After recalling general principles of small loop control function for Launch Vehicles (§ 3), adaptations of LaSer tool for analyses of small loop stability are presented (§ 4). Results for the studied case of P80 as first stage of a typical Launch Vehicle are illustrated (§ 5): robustness of P80 controller tuning w.r.t. Launch Vehicle bending modes is confirmed. LaSer tool capability in terms of sensitivity analyses to LV and small loop parameters is also evidenced.

2. Presentation of LaSer Tool

"LaSer" is an acronym standing for "couplage LAnceur & SERvogouvernes" (coupling between Launcher and Actuators)". LaSer software has been developed within a Matlab/Simulink environment (figure 2.1 illustrates the global architecture of the software).

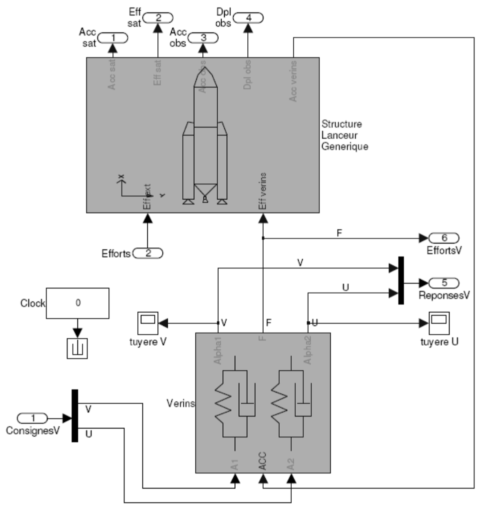

Figure 2.1: Laser Software overall architecture

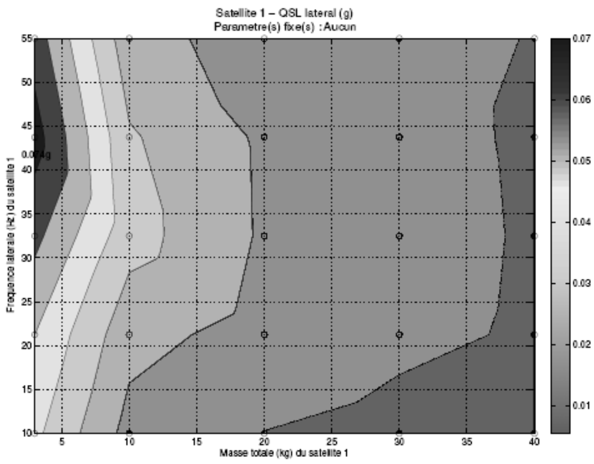

Figure 2.2: Typical parametric study results

2.1 General presentation of the tool

LaSer tool is fully dedicated to perform parametric dynamic studies covering a wide range of satellite characteristics: satellites models can be refined (Craig and Bampton formulation [6] – matrix representation using mass, stiffness and damping matrices) or simplified (effective mass formulation for each degrees of freedom). In the second case, the software includes a module to produce automatically the payloads models covering a specified domain. User can define a domain for the payload total mass, total inertia, center of mass location, characteristic frequencies, etc.

The launcher model is transmitted to LaSer in a matrix format (Craig and Bampton formulation). Then, the software couples other models (payloads, actuators) using interfaces nodes.

User can excite the global system with localized loads, condensed loads or even with deflection commands that drive the actuators.

The numerical system can be solved in time or frequency domain. The results treated by the post-processing module are usually accelerations and forces at payloads interfaces, but user can define specific outputs on the launcher or on the actuators. For example, in figure 2.2 is plotted the evolution of lateral QSL (quasi static load) of a payload as a function of its mass and lateral frequency. Several validation loops have been done on ARIANE 5 launcher. They have enabled to define rules in terms of junction modelling and modal bases size, leading at the end to an increased confidence in the tool reliability.

2.2 Application to P80 firing test prediction

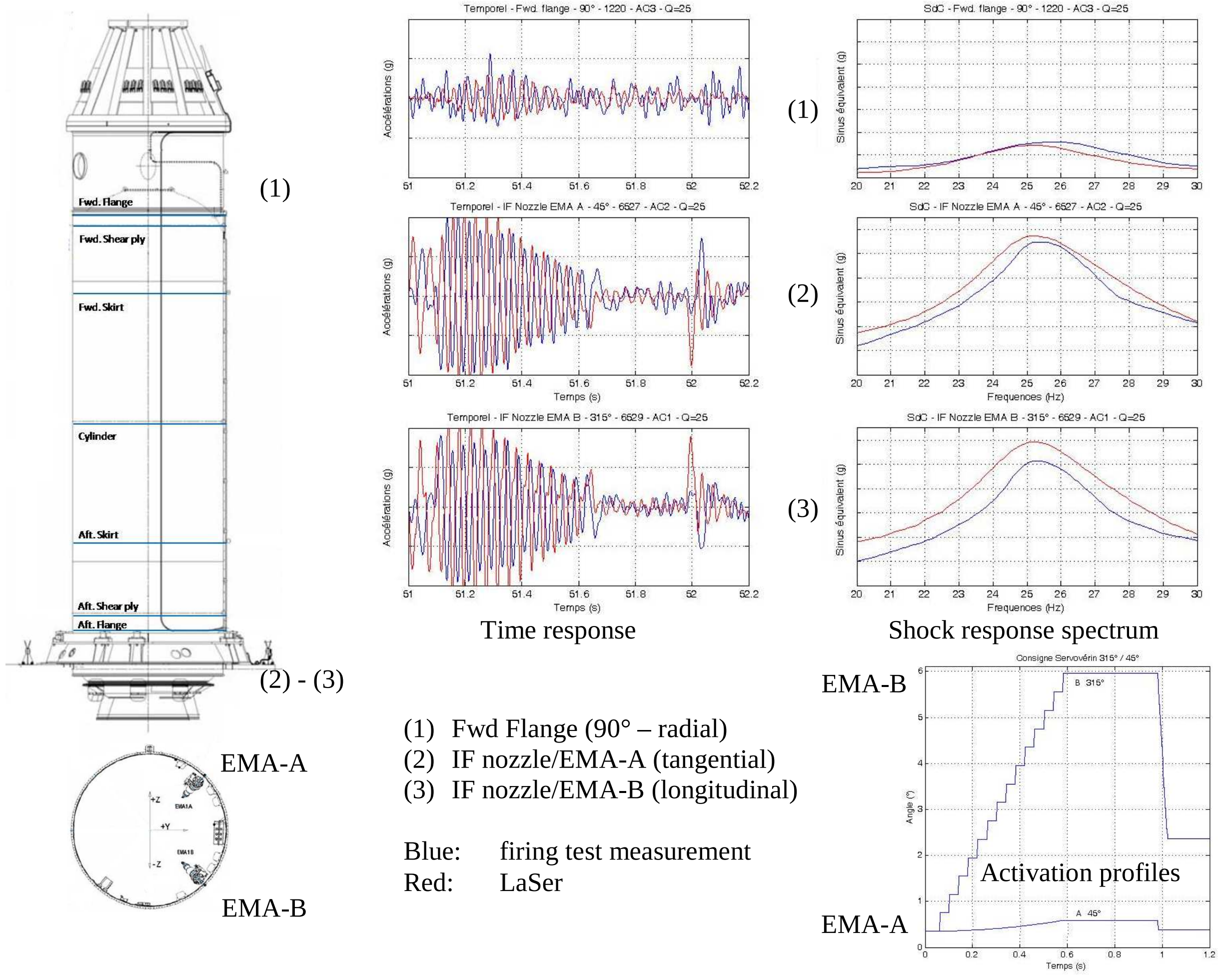

Figure 2.3: Dynamics responses of P80 to TVC actuations during firing test

As an example of LaSer tool application, one can focus on the prediction of the dynamic response of P80 to TVC deflection commands during Solid Rocket Motor (SRM) qualification firing test. This firing test has confirmed an expected coupling between TVC deflection command frequency and the pendulum mode of the nozzle. This technical issue has been solved through the small loop design and tuning (see § 3.3).

For this LaSer simulation, specific dynamic models of the P80 and of the test bench have been developed by CNES. Actuators models have been developed by the industry within a Simulink environment (see § 1). The coupling between the two is achieved by LaSer. For this computation, only the loads induced by the actuators activations are taken into account (thrust is not modelled). Figure 2.3 presents a summary of test and numerical results. Figure on the left presents the P80 stage in test bench configuration (only bench nose and rear attachment devices are represented).

The two actuators (named EMA-A and EMA-B) are acting in perpendicular directions. The main deflection angle was imposed on EMA-B. In a time frame of 0.6 seconds, the deflection command was increased up to 6° with 0.4° steps. From test and simulation results, one can observe a coupling between the actuators deflection response and the pendulum mode of the nozzle. LaSer computations are relatively close to the measurements.

A good correlation can be observed on several other locations (see for instance the Forward Flange) and during all the firing test duration. It nevertheless remains imperfect for some locations, mainly due to the absence of other phenomena in the model (thrust, acoustics, propellant burning, etc.). For low frequency dynamic simulation involving TVC activations, the model is considered as valid.

3. Launch Vehicles small loop control principles

3.1 Generalities about small loop function

Small loop function of a Launch Vehicle propulsive stage aims at achieving the required angular deflection of a nozzle. Command is sent by the On-Board Computer (OBC) on a communication digital bus. Small loop function is generally realized by a so-called Thrust Vector Actuation System, encompassing power supply, control electronics and actuators [2] & [3]. Two actuators are located perpendicularly to allow a 2-dof rotation of the nozzle (see figure 2.3).

Up to the end of the 90's, the need of large power actuators for European Launch Vehicles' first stages has led to the choice of hydraulic power sources associated to electrohydraulic actuators. On ARIANE 5 for instance, boosters' nozzles are actuated using such technology [4].

Development of high power Electro-Mechanical Actuators (EMA) has nowadays permitted to use such equipment on large scale boosters, allowing gains in terms of cost and maintenance. P80 implements EMA with more than 50kW input power [3]. Each of these actuators consists of a brushless permanent magnet synchronous motor that drives a roller screw through a gearbox. This way the rotational motion of the motor is transformed into a linear motion.

3.2 Small loop control structure

A typical and generic architecture of small loop controller can be represented, independently of the technology of the actuator (electro-hydraulic or electro-mechanical). Classical approach for the design of small loop control foresees multiple nested loops (cascade, [5]). Figure 3.1 hereafter illustrates such structure.

The inner current loop is generally associated to a much larger bandwidth than the other loops. It is not discussed in this paper.

Technical constraints impose to have a feedback on actuator position rather than nozzle position itself (which is the controlled parameter). LVDT sensor is generally used to measure the length variation of the actuator. For EMA, the motor angular position is measured using a resolver and derived to obtain a velocity feedback.

Tuning of the position and velocity feedback controllers allow to fix the main characteristics of the small loop dynamics [2]. Proportional Integral controller on position feedback is chosen to limit the static error that may be due to LVDT measurement. Velocity feedback allows to increase damping of the reference input tracking.

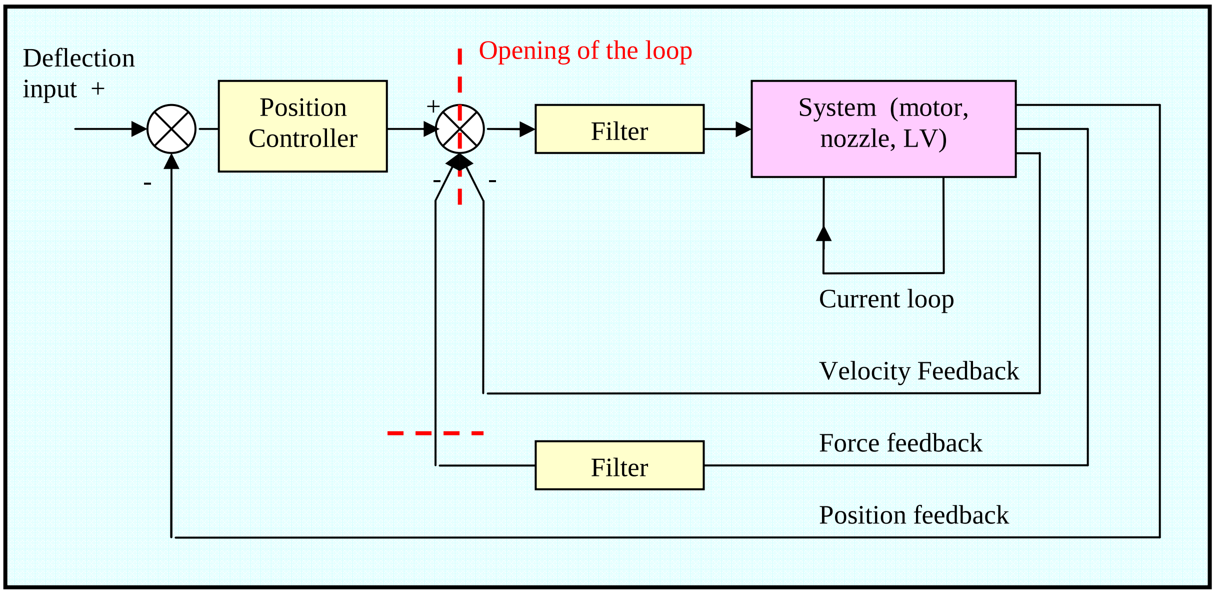

Figure 3.1: Classical structure of small loop controller

3.3 Force feedback

Limitation of the loads induced by the reference (deflection) input tracking can be achieved by a notching of the input signal around the pendulum frequency. Pendulum frequency is the frequency of the eigen-mode created by the nozzle and the chain of stiffness constituted by the actuator and its attachments.

Such a notch filtering is not efficient to deal with external perturbations. Moreover, an increase of the damping of pendulum mode can be required.

Differential Pressure Feedback (DPF) was initially introduced on ARIANE 5 electro-hydraulic actuators to limit the vibrations induced at Payload level [5], and to ensure a good perturbation rejection when nozzle was submitted to external aerodynamic perturbations. Such DPF consists in a measurement of the difference of pressure between the two chambers of an hydraulic actuator.

For electro-mechanical actuators, such as P80 ones, interest of force feedback can be evidenced when following condition is verified [2] & [3].

$$J_m >> \frac{M_{Load}}{N^2 \cdot \eta} \tag{1}$$

Where:

J_m	is the motor inertia (kg.m^2)
M_{Load}	is the equivalent mass of the nozzle, when system is modelled as the equivalent linear translation of a mass (kg)
N	is the reduction ratio of the actuator (rad/m)
η	is the screw efficiency (-)

(1) characterizes the condition where the mobile part of the actuator participates to the nozzle oscillations with relatively low amplitude, i.e. when actuator equivalent inertia is high w.r.t. the load (the nozzle). A force feedback is then useful to measure the load oscillations, and its introduction allows to manage their damping when needed. For P80, (1) is verified with a ratio much higher than 5 between the two parts of inequality.

A load cell consisting of strain gauges has been integrated in the actuator [3]. It thus allows measuring the axial force transmitted by the actuator to the launcher structure, and helps providing damping to the pendulum mode.

High pass filtering on force feedback allows to disable the damping effect in the position loop bandwidth and thus to maintain good tracking performances.

3.4 Small loop performances

Performances and robustness of a small loop can be divided in 3 categories:

- performances for (position) reference input tracking, and compromise with stability margins;
- perturbation rejection;
- load limitation capabilities.

Stability margins can be characterized through open loop frequency analyses. Time domain performances are usually characterized using a non linear model, while stability margins are evaluated with a linearized model.

In the following paragraphs, LaSer tool which implements a full non-linear model of both actuators is used to characterize stability margins. Such an approach allows:

- to use the same model for all performance evaluations of the system without simplifications;
- to account for the possible coupling between actuators axes in the analyses;
- to determine the linearity limits for the various signals of small loop, and evaluate the distortion induced by non-linearities above these limits.

LaSer tool also permits to couple the actuator model with a full FEM of a Launch Vehicle (using P80 as first stage) and to quantify the impact of bending modes on small loop performances and robustness.

Later-on in this paper, specific focus is made on the stability margins in open loop, but LaSer tool permits as well to characterize closed loop performances for reference input tracking.

4. Adaptations of LaSer tool for small loop control analyses in frequency domain

4.1 Development of LV dynamic model using P80 as first stage

A typical 4-stages Launch Vehicle FEM model has been developed, with P80 as 1st stage. This model is associated to flight configuration at the most critical time for low frequency dynamics of LV. It has been integrated in LaSer software tool and coupled with the actuators model from industry (see § 2).

4.2 Open loop Transfer Function analysis

Global stability of the small loop can be sufficiently assessed by looking at the inner loop opened at the command sent to the motor. Nevertheless, looking at each of the control loops opened individually can provide relevant information for assessment of robustness.

In the rest of this paper, current loop is considered as part of the plant, but its details are accurately modelled in the TVC actuators model integrated in LaSer.

Transfer function of the open loop is assessed by time domain simulations. Sine trains are sent in input of the chosen open loop for each frequency: amplitude and delay of the signal in output is then evaluated to identify the transfer function.

Due to non linearities present in the actuator model, some specific features have been implemented:

- quasi-linearity domain of each open-loop signal has been first assessed, in terms of input signal amplitude. Stability margins presented hereafter have been evaluated inside this domain (but studies outside this domain can be performed as well, with various amplitude of the signal, to assess non-linearities impact);
- amplitude and phase of the output signal is only considered for transfer function computation once a steady state response obtained. A few tenth of periods are necessary to achieve such a stabilized answer. In order to

reach this steady state faster, specific amplitude increase profile is implemented to limit the transient perturbations (see figure 4.1);

- to limit the effect of distortion, phase (i.e. delay) is computed at zero-crossing of each signal.

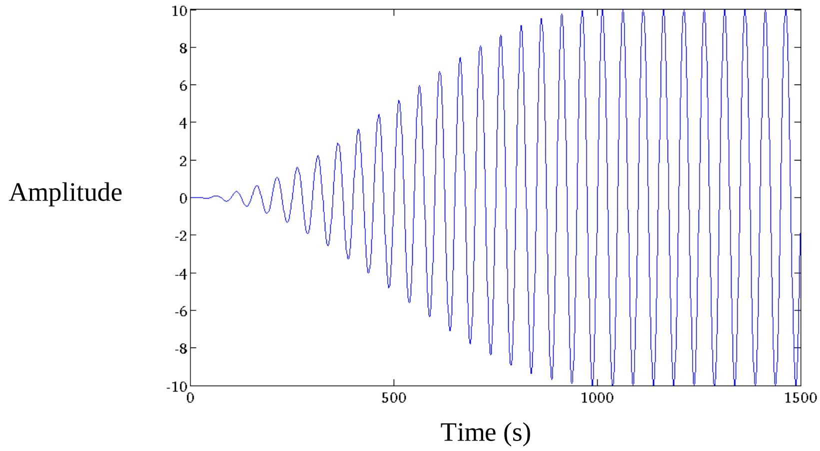

Figure 4.1: Typical input signal at low frequency for transfer function evaluation

LaSer permits to select the modes to be simulated in the dynamic model coupled with the actuator, through their effective mass w.r.t. a given node. In the rest of this paper, two models are used:

- first model (M50) includes only the 3 most significant modes w.r.t. the rear part of the LV. It is thus a relatively light model, allowing preliminary analyses;
- second model (M1) includes all the modes having an effective mass higher than 1% of the whole Launch Vehicle mass, at one of the nodes at the rear part of the LV. This model includes more than 60 flexible modes.

LaSer also permits to vary some of the characteristic parameters of the system. For instance:

- large variations of actuator attachment stiffness have been tested in order to assess robustness of small loop stability margins towards variations of pendulum mode frequency;
- large variations of Payload mass, centring, inertia and lateral frequencies have been tested in order to assess robustness of small loop stability margins over a Launch Vehicle mission domain.

In all cases, small loop is open for one of the actuators controller only, while the second actuator is maintained in closed loop. Thus, coupling between axes is accounted in the presented results.

5. Results

5.1 Stability margins obtained in nominal case

Figure 5.1 presents the Black locus obtained using LaSer, for M1 model, opening the loop between the force and velocity feedbacks (see figure 3.1).

One can observe that, despite some limited *noise* due to numerical accuracy of the method, results are quite consistent with expected linear ones. For instance, one can compare figure 5.1 to global open loop linear Black loci plotted in [4] for ARIANE 5 EAP.

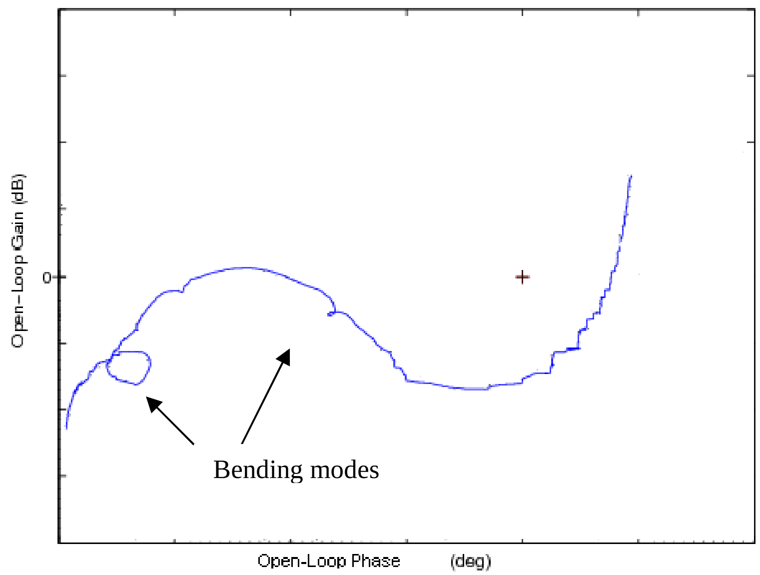

Figure 5.1: Nominal open loop Black locus of position & force loop – M1 model

Results can also be compared to experimental results presented in [4] and obtained on representative mock-up: LaSer has the advantage of authorizing a much more precise frequency discretization, while being as much representative as a model can be from real hardware (and including flexible modes).

Significant stability margins are also evidenced in figure 5.1. When comparing these margins (and the ones using M50 model) to those obtained by EUROPROPULSION and SABCA, using a linearized model of the small loop, it can be concluded that neither the non-linearities, nor the coupling between axes, and nor the bending modes of the LV, induce critical stability margin losses on the studied case. Same conclusion can be drawn for any of the locations chosen to open the loop.

One can finally observe well damped flexible modes of the Launch Vehicle, around the pendulum frequency margin. Same positive impact on the modes damping than the one observed in [4], when using a DPF on an hydraulic actuator, can be observed.

5.2 Sensitivity analyses to pendulum mode and Payload characteristics

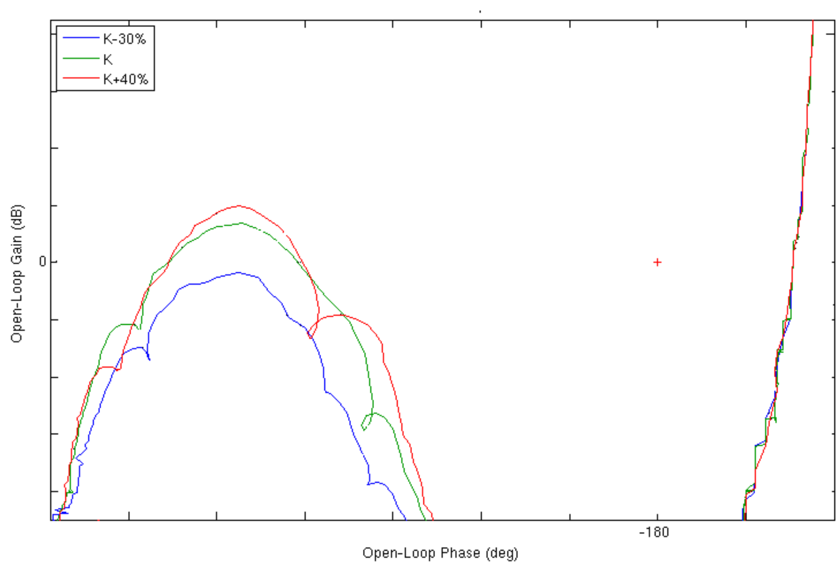

Figure 5.2: Black loci of position & force loop – Sensitivity to actuators attachment stiffness

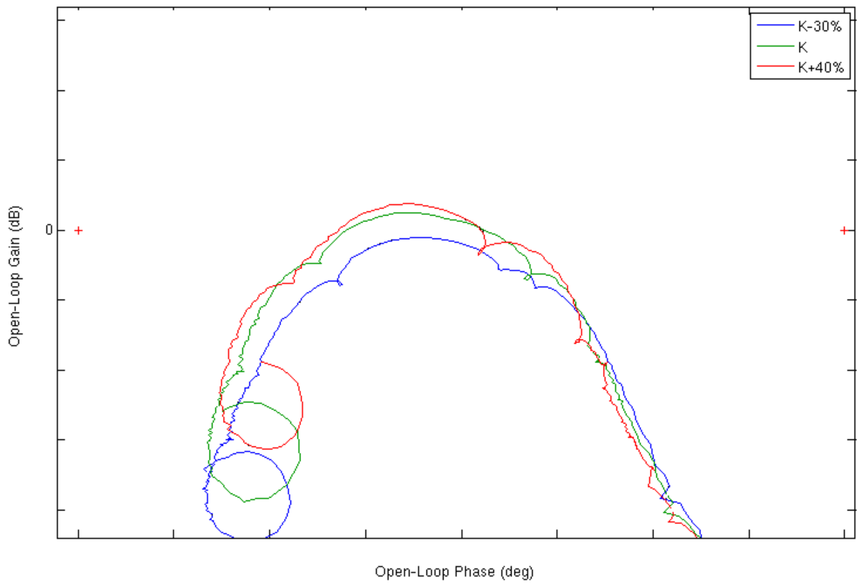

Figure 5.3: Black loci of force feedback loop – Sensitivity to actuators attachment stiffness

LaSer allows to vary input parameters of both actuators and LV models.

Figures 5.2 and 5.3 illustrate the sensitivity analysis performed to the pendulum mode frequency. Actuators attachment stiffness has been varied of -30/+40% in order to assess the impact on stability margins. Results are presented for the same open loop as figure 5.1 and for the force feedback open loop. They demonstrate that stability margins remain large despite such variations.

Same kind of sensitivity analyses have been performed, varying Payload model parameters (see § 4). Large variations of these parameters have a very limited impact on the small loop stability margins, evidencing high robustness of the controller w.r.t. LV characteristics variations.

6. Conclusion

In this paper has been presented an approach permitting the re-use of a tool (LaSer), initially aimed at studying low frequency dynamics of a Launch Vehicle, for stability analyses of its TVC control loop (so-called *small loop*).

Such an approach allows to account for phenomena usually neglected (non linearities) in robustness assessments, or leading to high complexity of models (bending modes, coupling between axes).

A study case of P80 (associated to a typical LV in flight) has been used to demonstrate the capacity of the method. Nominal and scattered Black loci can be computed for different open loops, while coupling the TVC model with LV FEM of a chosen complexity. High flexibility of this tool is thus evident. Same approach can easily be extended to other small loop performances than stability margins (time domain performances, etc.).

This study has also consolidated the confidence in the robustness of the P80 TVC control loop, demonstrating significant margins despite large variations of LV parameters.

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