A Parametric Study on Ignition Transient of Solid Rocket Boosters for Future European Launchers

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Abstract

The start-up of solid rocket motors represents a critical phase during their whole operational life, that may induce severe impact on the payload comfort and on the dynamic operational environment of the launch vehicle. This paper is aimed at providing a first assessment of the ignition transient with the SPIT code of the new large monolithic SRM foreseen in the future configuration of VECEP upgraded first stage, that share the concept to be an over-loaded versions of the current VEGA first stage P80. The SRM configuration selected is inspired to the P105, VECEP first stage, designed as a stretched version of the P80 SRM, with an aft-finocyl configuration and the same igniter and nozzle configuration of the P80. The parametric analysis considers the impact on the SRM behavior of different kinds of pressurizing gas, exploiting the experience and know-how achieved during the VEGA development phase, with a conservative assessment based on the outcomes of the P80 firings analysis. An accurate analysis of the P80 firings, in fact, indicates that a conservative assessment of the dynamic environment induced during the first phase of the SRM start-up can be obtained assuming a mixture of helium with a small percentage of nitrogen as pressurizing gas. Results for the P80 XL stretched tentative configuration indicates that the use of helium as pressurizing gas is mandatory for controlling the SRM behavior during the ignition transient.

1 Introduction

The Ignition Transient (IT) of Solid Rocket Motors (SRMs) is characterized by strong unsteady phenomena occurring in a very short period of time. It starts with the first electric signal given to the igniter charge and ends just after the ignition of the entire grain surface, when the quasi steady state conditions in the bore are reached (usually after from 0.2 to 1 seconds, depending on motor size and configuration). In spite of the short period of time taken by this operative phase, its impact on the launch vehicle design and operation can be relevant. In fact, the IT has significant implications not only from the point of view of the SRM start-up and the thrust delivered by the SRM during this crucial operative phase, but also for the launch vehicle operational requirements and structural verifications. The availability of reliable and efficient IT simulation models, able to properly predict and analyze the SRM behavior, allows leading the SRM design towards the accomplishment of system requirements already at the preliminary design phases. Indeed, many times unacceptable IT behaviors were detected in an advanced development stage (i.e. during the first static firing tests), when remedies and/or design modifications could be very expensive and with a big impact on the project time schedule [1].

Aim of the present study is to present a parametric analysis of the effects of the SRM configuration on the start-up phase of the motor, with a particular attention on the onset of pressure oscillations during the ignition transient, on the base of the experience gained with the P80 firings, static firing tests and flights. In fact, the reference configuration will be an aft-finocyl SRM with design characteristics similar to the P80 SRM, and its XL stretched versions (i.e. P105) foreseen in the concepts of the future evolutions of VEGA [2] and in the first definitions of the Ariane 6 concept [3, 4]. In particular, the attention will be focused on the VECEP upgraded first stage SRM, which is part of the VEGA Evolution and Consolidation Programme (VECEP) that has the aim to further increase the performance of VEGA, reaching a capability of greater payloads insertion in the reference orbits. Preliminary system analyses performed by ELV, prime contractor of VEGA, showed an initial possible step which foresees the first stage propellant increase from 80 to about 105 tons (and the second stage propellant increase from 23 to about 40 tons), establishing therefore the bases for the development and qualification of new technological demonstrators, able to increase the performance of VEGA launch vehicle [2].

This work exploits all the experience and know-how achieved at Sapienza University of Rome by the research group working on solid rocket propulsion, in the simulations of the start-up phase of solid rockets, especially in the frame of the VEGA programme and VEGA solid stages development. The parametric study of the SRMs ignition transient will be performed with the Q1D unsteady model SPIT.
- Solid Propellant rocket motor Ignition Transient, successfully validated against all the European SRMs (Ariane 4, Ariane 5, Zefiro 9, Zefiro 16, Zefiro 23 and P80) and officially adopted in the frame of the VEGA program, for the predictions and reconstructions analyses of the solid stages ignition transient [5–19]. A full description of the models and sub-models is not in the scope of this work and can be found in Refs. [5, 8, 9, 20, 21].

The paper is organized as follows: section 2 provides an overview of the numerical simulations of the ignition transient of the P80 static firing tests (P80 DM and P80 QM) and of the P80 flights (P80 VV01 and P80 VV02), that are considered as reference for the model set-up for the preliminary assessment of the P80 XL stretched ignition transient; section 3 reports and analyzes the preliminary assessment on the P80 XL SRM ignition transient.

2 P80 Ignition Transient: Static Firing Tests and Flights

This section discusses the numerical simulations of the P80 SRM considering both the static firing tests performed during the development phase of the VEGA Programme (P80 DM and P80 QM) and the two qualification flights of the VEGA launch vehicle, held with success in the 2012 and 2013 (VV01 and VV02). The aim is to re-cap the experience gained with the P80 motor firings and to define a conservative model set-up of the SPIT code for the assessment of the P80 XL stretched ignition transient, as a tentative configuration for the P105 VECEP upgraded first stage. In fact, the P105 will exploit and share with the P80 similar SRM configuration, technologies and components, so that it can be considered in a preliminary assessment, a stretched version of the P80 SRM.

Because of the strong unsteadiness nature of the ignition transient, which involves low and high operative pressure, the experimental data reported for comparison with the numerical simulations consider the following set of measurement gauges: high pressure transducers (HP), low pressure transducers (LP) and dynamic pressure transducers (DP).

Therefore, the references for the comparison with the numerical simulations are different during the different phases of the SRM start-up. In fact, during the first phase of the ignition transient, the reference is for most of the times, the dynamic pressure transducer, up to its saturation. Whereas, after this first phase, the reference is the high pressure transducer. In all the cases, the low pressure transducers appear to be in a strong delay with respect to the others measurements because of the high pressure rates involved in the SRM start-up. All the data are represented in a non-dimensional form for confidentiality reasons.

Figure 1 shows the comparison of the SRM head-end pressure during the ignition transient of the P80 DM, which was fired in November 2006, in the test bench at CSG, in French Guyane. The motor was filled with helium, in order to avoid the onset of pressure oscillations during the SRM start-up experience on Zefiro 16, the technological precursor of VEGA SRMs, as results of the studies performed by the work-group at Sapienza University of Rome, successfully validated and consolidated by the static firing tests of the Zefiro 23 DM (June 2006) and Zefiro 9 DM (December 2005).

In Figure 2, the detail of the SRM pre-ignition transient phase is depicted, showing in particular the time instant of the nozzle seal breakage as outcome of the numerical simulation.

In both Figure 1 and Figure 2, two numerical pressure curves are compared with the experimental data: one obtained considering a pure helium ambient in the combustion cham-
ber and a second one, which assumes a mixture of helium with a small amount of nitrogen, which can be considered a more conservative set-up for assessment of the first phase of the ignition transient, outcome of the analysis of the VEGA qualification flights VV01 and VV02, as will be detailed in the following. It is worth noting that the different types of pressurizing gas has an effect only in the first part of the ignition transient and becomes completely negligible in the rest of the SRM ignition.

Figure 3 depicts the ignition transient of the P80 QM SFT, comparing the experimental data coming from the acquisition system of the test bench and the numerical simulation performed with the SPIT model. P80 QM SFT was intentionally designed in order to verify the helium solution, as design option for the suppression of the pressure oscillations onset during the SRM ignition transient of the VEGA SRMs. In order to obtain this aim, since one of the goals of the SFT was the validation of the prediction models used in the frame of the VEGA Programme, the SRM was charged with nitrogen as pressurizing gas, to compare the motor start-up with respect to the one obtained with the P80 DM. The SFT was held at CSG, in French Guyane in December 2007. In particular, comparing Figure 2 (P80 DM charged with helium) and Figure 4 (charged with nitrogen), the efficacy of the helium in the suppression of the pressure oscillations during the first phase of the SRM start-up is evident, as well as the SPIT model capability in capturing in an accurate manner the whole ignition transient of the SRM. This fact is also evident by the comparison of the derivative in time of the dynamic pressure transducer of the P80 DM SFT (charged with helium) with the one of the P80 QM SFT (charged with nitrogen).

Figure 4: P80 QM SFT: Experimental Data and Numerical Simulation - Pre-Ignition Transient

As result of the P80 DM and QM SFTs held with success, as well as the outcome of the SFTs performed for the Zefiro 23 and Zefiro 9 SRMs, both the VEGA qualification flights have been performed adopting the helium as pressurizing gas for all the VEGA solid stages.

Figure 6 depicts the motor pressure during the ignition transient of the VV01 flight, comparing the experimental data with the SPIT simulation. Also for this case, two simulations are reported as reference and comparison with the experimental data: the pure helium case and the mixture of helium with a small amount of nitrogen, that is considered to be more conservative during the first phase of the IT for the dynamics environment generated by the SRM ignition and also quite well...
Figure 6: P80 VV01 Flight: Experimental Data and Numerical Simulation

...correlated with the measurements. In particular, the reconstruction of P80 IT for the VEGA VV01 flight has shown also a dynamic environment at the SRM start-up that is not compatible with a full loading of helium inside the combustion chamber.

Figure 7: P80 VV01 Flight: Experimental Data and Numerical Simulation - Pre-Ignition Transient

...In fact, other causes that can result in such kind of a SRM behavior during the first phase of the SRM start-up, e.g. an uncertainty of the igniter mass flow rate, appear to be not sustained either by the analysis of the experimental data or by the numerical simulations. Actually, the uncertainty of the igniter mass flow rate in the earliest time instants of the SRM start-up is retained responsible for the lack of the agreement of the numerical simulations with the experimental data, in the initial time instants of the IT, for all the firings. Anyhow, this uncertainty has a very second order effect in the remaining part of the pre-IT, where the head-end pressure trend is dictated mainly by the pressurizing gas type. Therefore, from a system/project point of view, the worst case scenario in terms of pressure-thrust oscillations, as well as induced acceleration during SRM start-up, has to take into account the possibility that the pressurizing gas may not be completely helium in terms of composition. This fact is also sustained by the re-analysis of the P80 DM SFT, as shown in Figure 1 and Figure 2, for which a conservative model set-up for the simulation of the SRM ignition transient based on the assumption of a non-pure helium ambient in the combustion chamber has a good correlation with the experimental data.

Figure 8: P80 VV02 Flight: Experimental Data and Numerical Simulation

The uncertainty related to the pressurizing gas composition is assessed also in Figure 8 and Figure 9, that depict the VV02 flight experimental data and numerical simulations. Whereas for the preceding cases, the SPIT model set-up was tuned intentionally in order to match in detail the experimental data, for a reconstruction of the firing, for the VV02, the SPIT model set-up is kept the same of the VV01, in order to demonstrate the prediction capabilities of the model. In particular, this means that a part from the input parameters related to the igniter operative conditions, the propellant grain burning rate properties, and a small recalibration of the nozzle seal breakage (which occurred at a pressure slightly higher than nominal), no tuning is imposed to the model to match the experimental data. Though this fact, a very good correlation of the numerical simulations with the experimental data is obtained for both the whole pressure profile during the ignition and, in particular, for the first phase of the SRM start-up. Concerning this part of the ignition transient, the case with a small amount...
of nitrogen present inside the helium ambient of the chamber appear to provide a better and conservative correlation of the first phase of the SRM start-up.

In Figure 10 and Figure 11, the thrust developed by the SRM during the ignition transient is evaluated for the P80 DM, QM, VV01 and VV02, in the different configurations shown in the previous figures: nitrogen case for the P80 QM and helium and helium with a small amount of nitrogen for the P80 DM, VV01 and VV02.

In the case of use of helium, instead, a reduction of the thrust oscillations in terms of one order to magnitude with respect to the case of nitrogen can be achieved. It is worth noting moreover, that the case with a mixture of helium with a small amount of residual nitrogen present in the chamber provides both a good correlation with the experimental pressure measurements, as well as a conservative assessment for the thrust and dynamic environment generated by the SRM. In particular, comparing one the other the case with helium and helium with small amount of residual nitrogen, a small but present amplification of the thrust oscillations present at the SRM start-up during the first time instants can be ascertained.

3 P80 XL stretched Ignition Transient Preliminary Assessment

For the preliminary assessment of the ignition transient of the P80 XL stretched SRM, the experience, know-how and model prediction capabilities gained in the analysis of the P80 firings is exploited. In fact, as foreseen to date, having as refer-
ence the VECEP upgraded first stage, the P105 represents the evolution of the P80 SRM which inherits from this SRM the design for many of the SRM components (propellant composition, aft-finocyl propellant shape, low-weight casing, nozzle configuration and materials, ...) and the production technologies.

In particular, in order to provide a first assessment of a possible design options for the P105 configuration, a first tentative P80 XL stretched configuration has been designed on the base of the P80 SRM and a stretched version of such configuration, hosted in a longer casing. This tentative configuration is based on an aft-finocyl propellant grain, and similar to P80 design for the igniter and the nozzle. In the following, the impact of different kinds of pressurizing gas on the ignition transient is evaluated on the base of the options tested in the frame of the VEGA Programme: nitrogen, helium and the case of helium with a small amount of entrapped nitrogen (which is assumed a conservative case in the light of the analysis performed in section 2).

Figure 12 shows the ignition transient phase for the cases considered, assuming the model set-up gathered from: the P80 VV01 and VV02, for the case with helium and mixture of helium and nitrogen; for the P80 QM for the case with nitrogen. Figure 13 shows the detail of the first part of the ignition transient, for the assessment of the SRM pre-ignition transient phase. The case with nitrogen presents the onset of relevant and sustained pressure oscillations during the first phase of the IT, as for the P80 QM, that is a peculiar characteristic of the ignition transient of aft-finocyl SRMs with the use of this kind of pressurizing gas. Whereas, the case with helium and mixture helium/nitrogen are not characterized by relevant oscillatory phenomena during the first part of the SRM ignition phase.

Figure 14 shows the thrust curves depicted in Figure 14 and Figure 15, both expressed in terms of the ratio of the thrust divided by the thrust in quasi-steady state conditions at the end of the SRM start-up.

In Figure 14 and Figure 15, the following remarks can be outlined. The case with nitrogen as pressurizing gas presents...
thrust oscillations of the order of 10% with respect to the thrust value delivered by the SRM at quasi-steady state conditions (the delivered thrust is of the order of $2500 \div 3000$ kN at the end of the ignition transient for this class of SRMs).

In case of use of helium or a mixture with helium and some percentage of nitrogen (for a conservative assessment), the thrust oscillations during the first part of the SRM start-up are of the order of 1-2% of the thrust delivered in quasi-steady state conditions. In all the cases, a small but present thrust oscillation reflects the excitement of the first chamber acoustic mode caused by the nozzle seal breakage. It is worth noting that the amplitude of the pressure and thrust oscillations during the SRM start-up depends directly upon the amount of nitrogen/helium utilized as pressurizing gas in the SRM.

4 Conclusions

A preliminary assessment of the ignition transient of a tentative configuration of the P80 XL stretched SRM, with reference to the P105 upgraded VECEP first stage, is performed and discussed in this paper. This preliminary assessment is rooted on the experience and know-how in the ignition transient simulations and analysis achieved in the frame of the development and qualification phase of the VEGA launch vehicle. The tentative P80 XL stretched SRM configuration has been built-up considering an overloading of the P80 SRM propellant grain configuration and assuming, for a first assessment, a design of the igniter and the nozzle similar to the ones of the P80 SRM. In particular, in order to perform a preliminary and conservative assessment of the ignition transient of this SRM configuration, a re-analysis of all the data available from the VEGA firings (SFTs and flights) has been performed. On the base of this analysis, for the P80 XL stretched the effects on the ignition transient of the composition of the pressurizing gas is investigated considering the following three options: nitrogen (as P80 QM), helium (as used in the VEGA SRMs) and a mixture of helium with a small amount of nitrogen (which represents a conservative assessment of the motor start-up induced environment in the light of the analysis of all the P80 firings: SFTs, DM and QM; and flights, VV01 and VV02). The analysis shows that as for the P80, the choice of nitrogen as pressurizing gas entails relevant pressure and thrust oscillations during the motor start-up, of the same order of magnitude of the ones experienced during the P80 QM SFT. Therefore, such kind of design appears to be few compatible with the necessary requirements for the dynamic loads transferred to the launch vehicle structures and of comfort of the payload. As conservative estimation of the pressure oscillations onset during the SRM start-up with respect to the P80 firings, the case with helium with small percentage of nitrogen shows for the P80 XL stretched configuration a start-up with small pressure and thrust oscillations, in line with the ones experienced by the P80 DM, VV01 and VV02. Certainly, some other design options, different from the ones consolidated in the P80 experience and which may play a role on the SRM start-up, have not been considered in this preliminary analysis, such as the igniter design and the nozzle seal breakage. Anyhow, these design options have second or order effects on the ignition transient behavior of the SRM and moreover, their choice is mainly dictated by the know-how of the technology already consolidated in the frame of the VEGA Programme.

Therefore, since the scenario expected to date for the solid rocket boosters of the future European launch vehicles, the VECEP Programme and the Ariane 6 launch vehicle development, involves aft-fincyl SRMs which are overloaded versions of the P80 SRM, a careful design has to be considered for the SRM start-up phase. In particular, even if the fine design selection for those SRMs has not been carried out, the use of the helium as pressurizing gas appears to be mandatory for the suppression/control of the dynamic environment generated at the SRM start-up for such kind of SRM configurations. Moreover, considering the multi-P configuration foreseen for the Ariane 6 launch vehicle, the presence at the boosters start-up (the launch vehicle lift-off) of relevant pressure and thrust oscillations, possibly slightly shifted in time of some milliseconds because of the dispersion of the single SRM ignition phase, has to be carefully accounted and evaluated because of their impact on the launch vehicle control system.

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VEGA launch vehicle has been developed within an Eu-
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REFERENCES


