Parametric Study of SRMs Design Options affecting Motor Start-up and Onset of Pressure Oscillations

M. Di Giacinto**, E. Cavallini***, B. Favini** *and J. Steelant***
**Dept. of Mechanical and Aerospace Engineering - Sapienza University of Rome*
Via Eudossiana 18, 00184 - Rome, Italy
** *ESA-ESTEC*
Keplerlaan, 1 - 2201 AZ Noordwijk, The Netherlands

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 at 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 0.2 to 1 seconds). In spite of the short period of time taken by this operative phase, its impact on the launch system 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 performances, but also for the launch vehicle operational requirements and structural verifications. Therefore, the development of new SRMs requires to improve the understanding of the IT physical mechanisms and to clarify their origins and dependencies. Moreover, the availability of reliable and efficient IT simulation models to properly predict and analyze the SRM behavior will allow to lead the SRM design towards the accomplishment of system requirements already at the preliminary design phase. Many times unacceptable IT behaviors were detected at an advanced development stage (i.e. at the firsts Static Firing Tests), when remedies and/or design modifications could be very expensive and with a big impact on the project time schedule.

Aim of the present study is to present a wide parametric analysis of the effects of the main SRM design options on the SRM start-up phase, with a particular attention on the onset of pressure oscillations during the ignition transient.

2. Q1D SRM Ignition Transient Model

This section describes the SPIT (Solid Propellant rocket motor Ignition Transient) model used for the accomplishment of the parametric analysis presented in this work. SPIT model has been developed during last decades by the work-group on solid rocket propulsion at Sapienza University of Rome, leaded by prof. M. Di Giacinto and B. Favini, successfully applied to all the modern European SRMs (Ariane4, Ariane5, Zefiro9, Zefiro16, Zefiro23 and P80FW) and largely adopted in the frame of the VEGA program for the performance predictions and reconstructions and analyses of the VEGA SRMs ignition transients [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14].

The used gasdynamic model is an unsteady quasi-1D Euler flow model with mass addition and geometry evolution in space; the flowfield domain includes the entire nozzle. The following hypothesis are considered: single phase, non-reacting mixture of perfect gases; the properties of each gas are properly taken into account and the evolution of the mixture composition too; very fast chemical reaction occurring in a ideal thin layer at the propellant surface; friction effects are considered just until the grain ignition. The presence of slots and submergence region is not considered in cross sectional area and their effects are considered as mass and energy exchange terms with the main flow. Then, the classical conservation equations are formulated. The model is based on a set of ordinary differential equations deduced from a volume averaging of the mass and the energy conservation equations. The initial conditions are imposed by the initial geometry of the propellant surface, the initial state of the pressurizing gas inside the combustion chamber and the ambient conditions inside the diverging portion of the nozzle. The wall condition is assumed as boundary condition at both the head-end of the motor and at nozzle throat until the seal breaking. At this point the outside pressure value is imposed at the exit section of the diverging nozzle until the supersonic flow conditions at the nozzle end are acquired. The evaluation of the time history of the propellant surface temperature is obtained using an ordinary differential equation derived, coupling the unsteady 1D Fourier equation and the gas-solid heat convection equation. The ignition criterion is based on the assumption that the surface combustion takes place when the surface temperature reaches an assigned value, which depends on the local pressure value. For the igniter model the in influence of its designed parameters and operative condition on the motor start-up are considered. The model needs as input data, the overall igniter design options (external shape, dimension and location inside the motor chamber), igniter nozzle design options (number, shape, dimension, location and orientation) and igniter operational design options (thermodynamic data referred to the igniter combustion product, time evolution of the pressure inside the igniter, or any equivalent information, and inside the combustion chamber). Semi- empirical model are then applied for the estimation of the location and dimension of the impingement region on the propellant surface, as well as for the evaluation of the heat transfer coefficient in the impingement region and in the standard region. The adopted burning rate model is based on the de Saint Robert-Vieille for the quasi steady term and the Lenoir-Robillard formulation with the further modifications proposed by Lawrence and Lamberty, for the erosive burning term. The discretized model is based on an equally spaced finite volume approximation of the conservation equations recast in integral form. The adopted numerical method is a second order accurate ENO method coupled with an exact Riemann solver. This formulation allows dealing with flowfield affected by propagation phenomena with strong flow discontinuities and strong source terms. A full description of the models can be found in the Refs. [1, 2, 3, 4, 5].

3. Results

Two reference configurations are chosen because belonging to different SRMs conceptions for launcher applications (booster and stage/small booster) similar in terms of SRM design, respectively, to Ariane 5 solid booster (3 segments propellant grain: S1, star shaped, S2-S3 axysimmetric) and a VEGA stage (finocyl propellant grain), both charged with nitrogen as pressurizing gas in the baseline configuration. Hence, the baseline configurations are chosen intentionally with the following main characteristic: the baseline of the segmented SRM (case A) is not prone to relevant pressure oscillations during the IT, whereas the finocyl SRM (case B) is affected by relevant pressure oscillations during the first part of the motor start-up.

The parametric analysis considers the variation of the following design parameters: motor shape and geometry; igniter configuration; pressurizing gas type; igniter gas total temperature; propellant grain products total temperature; ballistics propellant properties; igniter mass flow rate (MFR) time history; initial pressurization level; seal diaphragm breaking level. The total number of simulations for each reference configuration is 15. In this abstract, we will summarize the results of the study focusing the attention only on the effect of the design options on the onset of pressure oscillations during the SRMs start-up phase. The complete analysis of the results will be provided in the full paper.

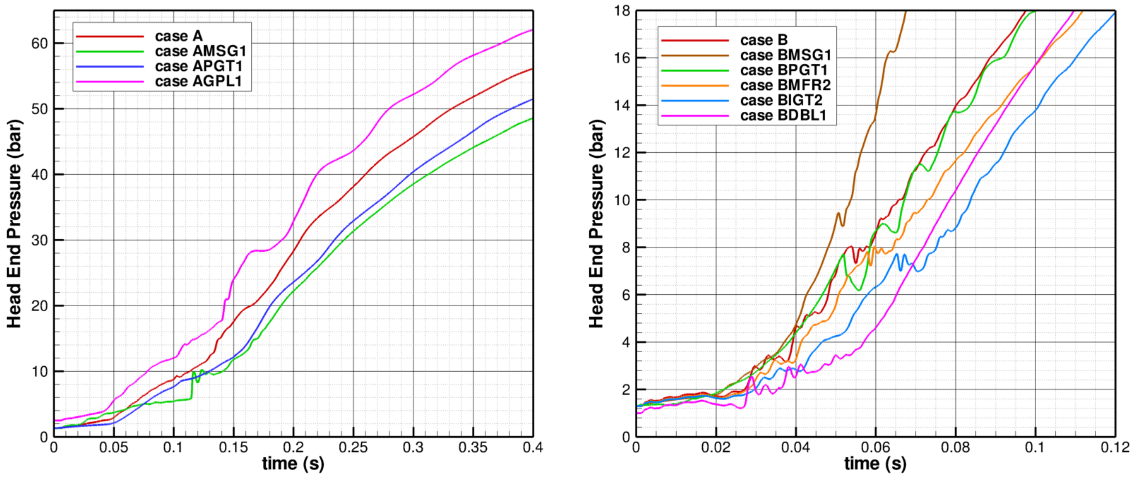
For the reference case represented by the segmented SRM (case A), an enhancement of pressure oscillations with respect to the reference case A is outlined for the following cases (see Figure 1(a)):

- before the nozzle seal breaking, for a complete redesign of the SRM geometry (AMSG1 case) with a star shape with a constant port area without slot and submergence region (for the same overall chamber volume and burning surface);
- after the nozzle seal breaking, in a similar way to the reference case B, with the use of a different pressurizing gas type (helium - APGT1 case) or to a higher pressurizing gas pressurization level (AGPL1 case).

For the finocyl SRM reference case (case B), affected by pressure oscillations during the first phase of the SRM start-up, the known driving mechanism, which brings to their onset, is modified by the following design options (see Figure 1(b)):

- the motor geometry (BMSG1 case): the use of a geometry of the grain propellant with a constant port area, instead of the finocyl configuration of the baseline (for the same overall chamber volume of burning surface) completely avoids the onset of the pressure oscillations, both before and after the nozzle seal breaking;
- the pressurizing gas type (BPGT1 case): the use of a different pressurizing gas (helium) other than the classical nitrogen completely destroys the mechanism of their onset before the nozzle seal breaking; whereas they become a few higher after the nozzle seal rupture;
- a different distribution of the igniter mass flow rate law in time for the same overall igniter mass and energy (BMFR2 case);
- a smaller igniter total enthalpy injected in the chamber (BIGT2 case);

- modifying the differential pressure of breaking of the nozzle, or considering a open chamber configuration (BDBL1 case).



(a) Segmented SRM - case A

(b) Finocyl SRM - case B

Figure 1: Design Parameters to Control the Pressure Oscillations Onset

As far as different aspects of the SRM IT are concerned, the following common results for the two reference configurations have been come out:

- a more energetic igniter (cases AIGT1 and BIGT2) brings to a more rapid ignition of the SRM and consequently to a higher pressure growth rate during the IT, with the same quasi steady pressure. Moreover, this goes with an higher pressure overshooting because of an enhancement of the erosive burning within the impingement region (opposite effects are present for the cases AIGT2 and BIGT2);
- a more energetic propellant (cases AGPT1 and BGPT1) does not alter in a relevant way the ignition of the propellant surface (except for the head end region), but enhances the quasi steady pressure reached at the end of the IT and consequently the pressure growth rate (opposite remarks for the cases AGPT2 and BGPT2);
- a faster propellant (cases ABPP1 and BBPP1) has not relevant effects on the ignition of the grain propellant surface (with the exception of the head end region of the SRM), whereas it enhances the quasi steady pressure reached at the end of the IT and consequently the pressure growth rate during the SRM start-up (opposite remarks for the ABPP2 and the BBPP2 case);
- a different MFR distribution (higher maximum MFR value for the same overall igniter mass - cases AMFR1 and BMFR1) decreases the ignition time of the entire propellant grain surface, increasing the flame spreading velocity, for the same quasi steady state pressure. But this goes with a decrease of the pressure overshooting because of a decrease of the erosive burning within the impingement region (opposite behavior for the cases AMFR2 and BMFR2).

We want to stress that except for known and trivial effects (e.g. the effect of a different a of the Vieille's law on the quasi steady pressure, or a more energetic igniter on a more rapid first ignition of the propellant and so on), the effects of a design parameter on the behavior of the SRM during the IT is to be carefully extrapolated as an effect valid in general, because it is strongly dependent on the SRM configuration under analysis (the phenomena involved in the SRM IT are strongly non-linear and inter-related each other). Thus, in order to argue or assess the implications of a design option on the SRM IT, it is safer to perform a parametric analysis for the SRM configuration of interest with a validated tool.

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