Demonstration of Pressure Oscillation Reduction in the Frame of New Launchers Development

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Abstract
The Ariane 6 program aims at developing a new launch system whose primary objective is to provide an independent access to space to Europe at a minimum recurring cost.

The new launcher is a PHH configuration meaning a three stages launcher with a lower composite propelled by a cryogenic stage with 2 or 4 solid rocket motors and an upper stage using cryogenic technology.

Beyond pure performance to recurring cost ratio, other competitiveness factors such as dependability, operability, overall life-cycle cost and environmental impact will play a decisive role for decision. In order to reduce the risks for the new solid rocket motors of the PHH configuration, different technology demonstrators, already started since 2010 under a French national frame, did continue within an ESA frame in 2013-2015. One of these demonstrators focused on the way, in design phases, to master and to minimize the level of thrust oscillations delivered by a solid rocket motor.
This paper gives a general overview of the main results then obtained through this demonstration program, including the final demonstrator firing test, obtained this year, which aimed to test promising solutions for Ariane 6 solid motors.

1. Introduction

In the frame of preliminary Ariane 6 design activities, Herakles (HKS) studied different launcher configurations for which first stages were based on solid propulsion. Actually the new launcher configuration is a PHH configuration meaning a three stages launcher with a lower composite propelled by a cryogenic stage with 2 or 4 solid rocket motors and an upper stage using cryogenic technology. At the European ministerial conference in December 2014, it was decided to design a common monolithic SRM for Ariane 6 and Vega C named P120C.
Among a lot of technical and economic issues identified for large solid rocket motor, a particular item was identified as justification of the technology maturation for a reduction of risks in the development phase to assure payload comfort.
Indeed, it's well known that a large SRM generally presents some pressure oscillation issues. A survey of SRM all over the world exhibits such instabilities during the motor operation. This point has been treated up to now either on Ariane 5 or Vega as a resulting 'drawback' to be accepted by the launcher system during the development. For Ariane 6, the goal is now to design the SRM with a low level of pressure oscillations at the preliminary design review, meaning to provide the associated justifications.
The main challenge was then to furnish concretes solutions to restrain pressure oscillations level to a low level in order to assure the payload comfort.

Thanks to numerous works initiated by R&D CNES/HKS/ONERA program, HKS has been developing a specific experience for the last 25 years addressing pressure oscillations issues. The feedback then acquired permitted HKS to

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build a global methodology which aims to study the different sources of pressure oscillations (PO) that may appear in a given SRM (cf [Ref. 1], [Ref. 2], [Ref. 3], [Ref. 4]). The main goal of the application of this methodology to a new SRM is to be able to predict the motor behaviour, and then to propose an improved design that limits the PO as soon as the preliminary design phase.

Based on this experience and due to the specific need for future monolithic SRM configurations, CNES initiated in 2010 a derived program named IDC (Instability of Combustion Demonstrator) in the PIA frame. This program did continue within an ESA frame in 2013 and ended in 2015. The challenging requirement was to reach a "Low-ODP design" for the future A6 first stage SRM and to validate it by a middle-scale firing test before the beginning of A6 development.

The purpose of this paper is to present the different steps that led us to propose promising solutions to drastically reduce pressure oscillation during motor operation. Once the methodology has been matured, a global SRM design was proposed for A6 and its validity recently tested *via* experimental demonstrations: a first assessment of the results exploitation is described.

2. PO logic of demonstration

From the beginning of the A5 program, the possibility to face pressure oscillation during the solid rocket motor operation was considered (cf. [Ref. 3] and [Ref. 4]). The encountered instabilities, which are closely related to the specific motor configuration, are expressed as pressure oscillations which, in turn, generate thrust oscillations. The vibrations affect the entire SRM, and this behaviour may become a serious concern for the comfort of the payloads carried by the launcher.
In a former SRM development program, the unsteady behaviour in terms of pressure oscillations is always measured after the first firing test. The aim of our studies is to include pressure oscillations issues in the preliminary A6 SRM design phases and to propose a concept that divides at least by 4 pressure oscillations amplitudes in comparison with SRM A5 launcher or actual P80 VEGA SRM.

To reach this goal, HKS showed that two kinds of potential instabilities sources must be avoided (cf [Ref. 4]):
- Hydrodynamics pressure oscillations, induced in first order by the SRM geometry,
- Combustion instabilities, and more precisely ITHAC phenomenon. This specific combustion instability is induced by the distributed combustion of aluminum particles in the combustion chamber (cf [Ref. 6] and [Ref. 7]).

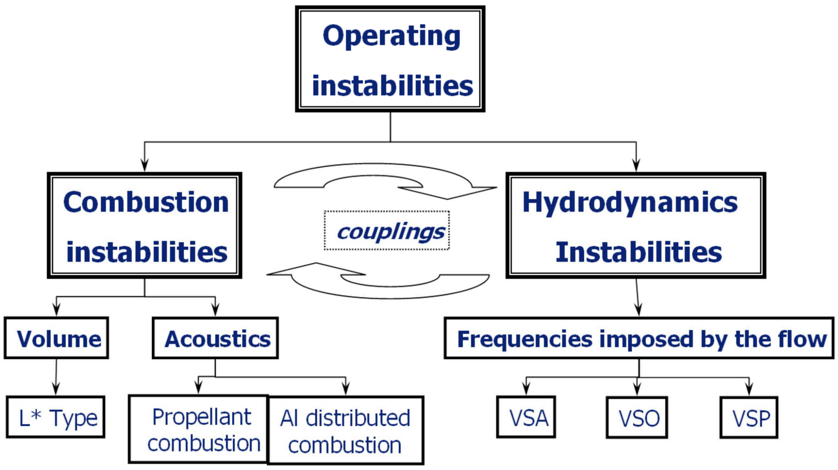


Figure 1: The various origins of PO

Consequently, to master these two instabilities types it's clear that specific attention has to be paid on both the SRM grain geometry and the propellant formulation. Solving the issues related to these two main sources of instabilities should lead to an almost stable behavior of the motor. The proposed design may also be robust: *i.e.* this guarantee of stability should not be modified by a little configuration evolution.

According with HKS methodology, preliminaries studies done on the firsts A6/Vega-C' SRM geometries underlined that concept of the retained monolithic aft finocyl grain was a good candidate to drastically reduce pressure instabilities occurrence.

- For the hydrodynamic concern, with a well-adapted geometry, it's possible to optimize geometrical details in order to limit vortex shedding formation.
- For the combustion concern, HKS and CNES had to work to develop an adapted propellant able to limit drastically the ITHAC's risks. This formulation will be further called the "Butalane® Zen".

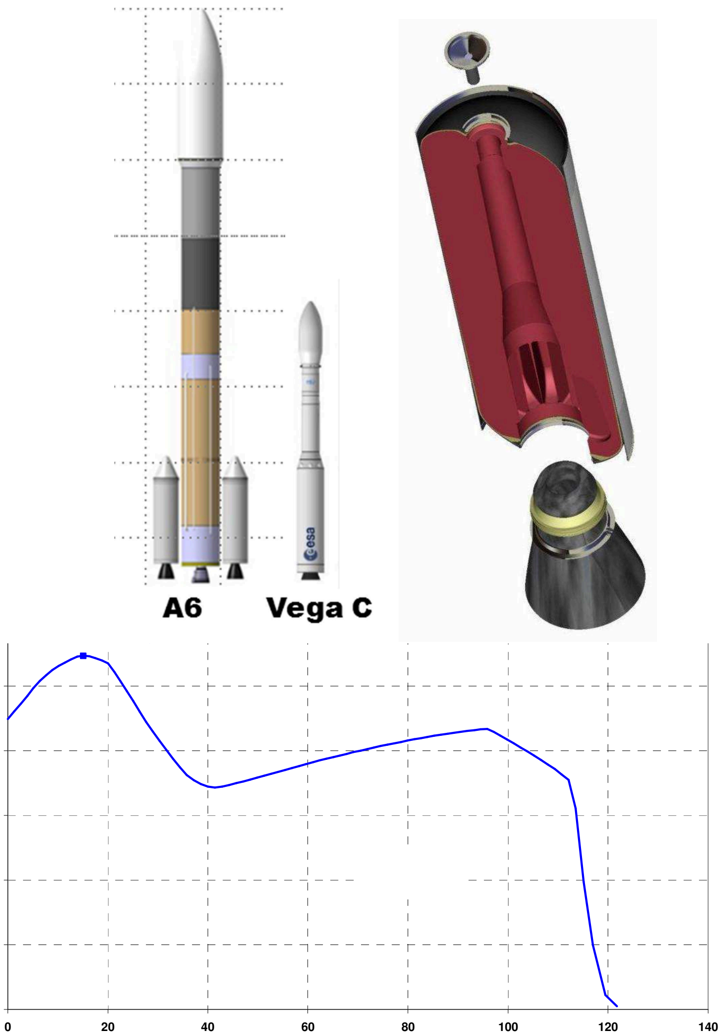


Figure 2 : Prototype SRM A6's global geometry and pressure evolution with time

Based on a representative monolithic A6 SRM geometry, this program was devoted to mature technologies to answer on both concepts: optimized geometry and adapted propellant formulation.

To reach this goal, this ambitious program was based on a robust logic. As HKS feedback showed it was necessary to validate step by step all predicting and theoretical unsteady behaviour, pertinence of each selected concept was first tested at laboratory scale before testing the final solutions at full scale.

It was all the more important as ITHAC combustion instabilities phenomenon was recently discovered by HKS. As a new potential instability source, the amount of knowledge on ITHAC was less important in comparison with the one dealing with hydrodynamic phenomena.

For these reasons the methodology employed was based on different tools and facilities testing including:

- Intensive numerical modelling to define optimized design/formulation in all operation phases
- Experimental mock-up for maturing geometrical and hydrodynamic instability concepts;

- Experimental evidence of distributed aluminum combustion effects on SRM stability, particularly characterization of ITHAC formation, for maturing instability concepts
- Analysis of the possibility to develop an industrial Butalane® Zen formulation for full SRM scale.

Once the solution has been matured, the last step of this program involved a mid-scaled demonstrator, called POD-y, at a representative scale in order to test the motor stability (PO < 10mbar) or quasi stability (PO< 30mbar), resulting from both geometry and Butalane® Zen propellant formulation.

3. Design to no ODP – IDC demonstrator

2.1 Concept maturations and small scale demonstration

Hydrodynamic stability concept

The selected geometry is a monolithic grain with an aft end finocyl knowing that:
- Monolithic SRM has a limited L/D ratio in order to limit Surface Vortex Sheddings (SVS);
- No protruding thermal inhibitor in order to avoid Obstacle Vortex Shedding (OVS);
- No marked angle in order to limit Angle Vortex Shedding (AVS).

The final grain design is a result of a compromise between the first performance needs for the motor imposed by the system and these stability criteria. The reference SRM grain design is presented in Figure 3.

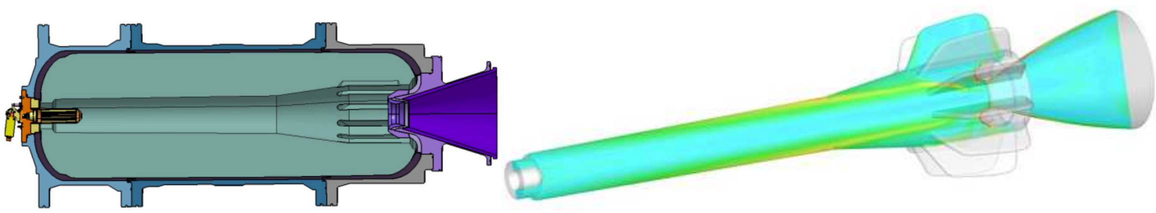


Figure 3: SRM A6's grain design and Stable flow (no vortices) obtained by computation

Before initiating intensive modellings, it is thus important to carefully examine the risk of PO occurrence. This is performed thanks a preliminary stability analysis.
Stationary studies (including surface regression, ballistic and thermodynamics data evolution) were then first performed to determine the steady-state behavior for the entire firing sequence. Concerning both sources these first analysis quickly underlined potential risk of vortex shedding occurrence in a quite restricted time interval located at the very beginning of the firing:

- AVS linked in this geometry to the angle formed when the cylindrical part evolves in the finocyl part of the grain;
- SVS linked to the motor length.

Concerning SVS, even if the monolithic shape has a limited length, the feedback on similar SRM geometries (P80's for instance) lead us to consider that the cylindrical part of the motor is long enough to let the possibility to SVS formation during the only first seconds of the operation. The risk of occurrence is judged weak after this time interval.
As well as SVS, AVS can occur during the first seconds of the functioning and disappear after this time interval.

However, criteria employed in this simplified approach only provide guideline information, and the analysis must be completed by performing more complex aerodynamic simulations to check the relevance of the preliminary one and to give values for PO levels and frequencies. Indeed, the only way to access the PO amplitudes is to perform numerical simulations, using the most suitable modelling.

The unsteady behavior has then been modelled and thanks to the stability analysis, computations focused on the beginning of the operation.

In order to have a good demonstration and to determine the possibility of hydrodynamic instabilities formation only, it was necessary at this point of the study to separate hydrodynamic sources from combustion sources. For this reason only propellant without or with limited Al combustion effects was considered.

Computations done confirmed the preliminary analysis in terms of hydrodynamic occurrence. Hydrodynamic instabilities (SVS) appeared on the very first time of the motor operation. It is characterized by the presence of the first longitudinal acoustic mode in the operating time interval where criteria are “in limit” to SVS formations. The associated risk was then maintained. In that case, levels could be notable. This type of instability rapidly disappears on the next computed instant.
These numerical results were in good accordance with the associated theoretical analysis and confirmed the main geometrical choices for the grain design.

To complete the analysis on this thematic, experimental tests were finally engaged. Based on the fact that hydrodynamic phenomenon can be observed and studied at a small scale, several experimental mock up with representative geometry were fired, with different propellants (aluminised or not).
Initial combustion chamber geometry has been well reproduced at small scale so that, these mock up could be considered as a good representation of the full scale one, at least on the major part of the operation.

Obtained results permitted to observe the absence of hydrodynamic instabilities during the entire firing test: a great correlation is obtained with associated computations and theoretical criteria.

As a conclusion on these first tests, preliminary results obtained at small scale underlined that it is possible to build a large SRM, where hydrodynamic instabilities are obviously limited. In this case, the risk is restricted to the beginning of the operation.
Knowing the leading-orders parameters that govern these kinds of instabilities, this design may be a reference for the A6 future geometry. Of course the future geometry should satisfy the desired thrust law, and should be adapted in consequence: a compromise will be mandatory.

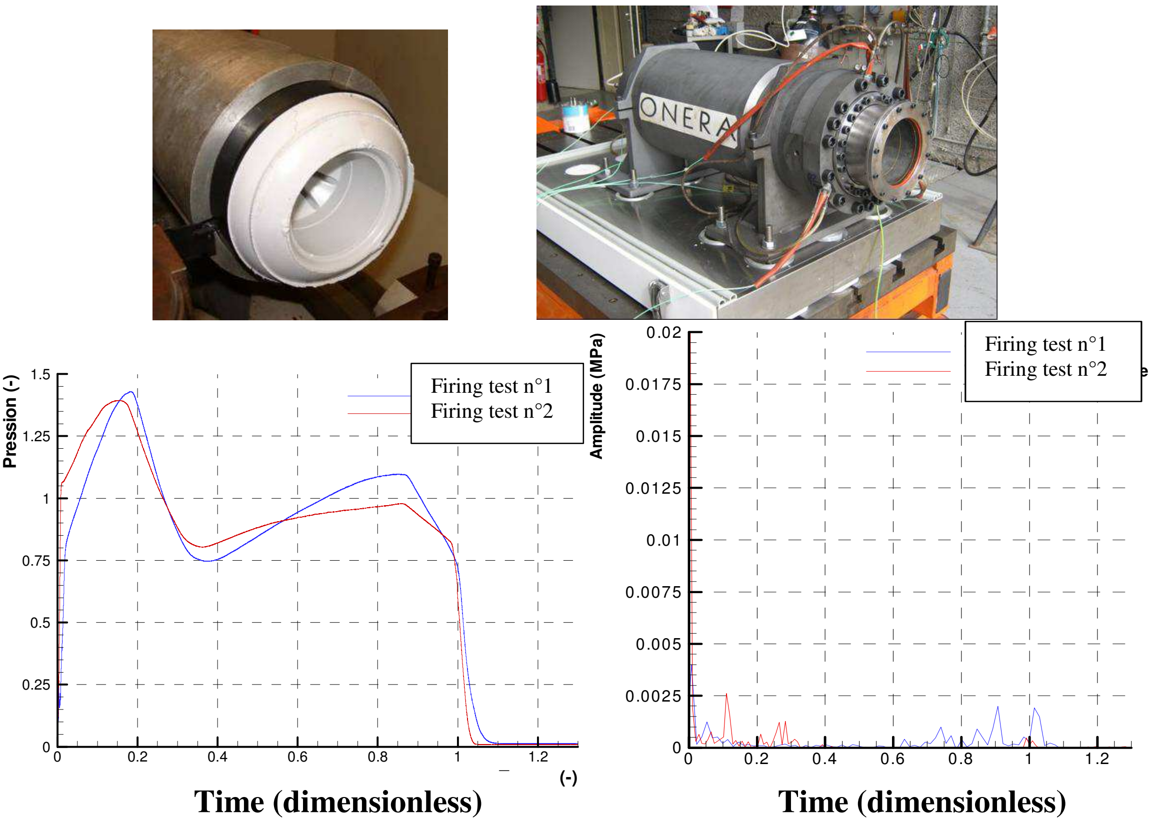


Figure 4: Different small scale mock up – Experimental validation (ONERA facilities)

Combustion stability concept

By considering the nature of the propellant, HKS has also defined criteria that indicate the possible presence of combustion instability, either a classical pressure coupling or ITHAC induced by aluminium distributed combustion in the combustion chamber.
It's identified that, with a classical formulation A6 SRMs belong to a class of motor that could generate THermo ACoustic Instabilities (ITHAC) during a noteworthy part of the operation, as soon as criteria on hydrodynamics formation are not satisfied anymore. This kind of instability is described in [Ref. 8] or in [Ref. 10], and once hydrodynamics issue are solved, it is the last remaining source of instability to master for a stable or quasi-stable SRM.

Reducing Al contribution in the combustion chamber could also have the advantage to reduce the risk of couplings between aluminium agglomerates and SVS formation at the beginning of operation and limit amplifying effects on PO levels.
Consequently, an adapted Butalane® aimed to reduce this kind of PO instabilities could be of high interest:

- This propellant may avoid ITHAC;
- In presence of residual hydrodynamic instabilities, a such formulation could drastically limit the coupling between VS and distributed combustion aluminum particles, and hence, associated amplifying effects;
- The motor could then be stable both in terms of hydrodynamic and thermo-acoustic instabilities during almost all phases of the steady operation.

As stated above, ITHAC combustion instability phenomenon was discovered by HKS quite recently and was after confirmed by ONERA analysis. As a consequence, the amount of knowledge at the beginning of the DEMO IDC project was less developed than for hydrodynamic instabilities.
Once the risks of combustion instabilities have been identified and assessed on the A6 SRM design, the main idea of the IDC program was first to acquire knowledge on Al agglomerates formation and combustion close to the propellant surface. This knowledge is then applied to define a propellant able to avoid ITHAC for the full scale motor.
Propellant formulation in that case was named "Butalane® Zen".

To define such a propellant, a large test plan was engaged to study and model distributed aluminium combustion in the SRM combustion chamber:

- Very large parametric two phases flow computations, including several hundred simulations, were performed in the final SRM's geometry to define main Butalane® Zen characteristics to reduce ITHAC contribution.
- Different types of propellants were studied in order to determine the main characteristics to formulate a Butalane® Zen for the A6 SRM.
- Experimental characterizations/bench test have been specifically developed to study on aluminium agglomerates formation near the propellant combustion with the use of ONERA specific devices. Obtained results then led us to determine driving parameters to conceive dedicated propellant which induce limited aluminium combustion contribution;

This formulation should also meet the required full scale ballistic and mechanical performances.

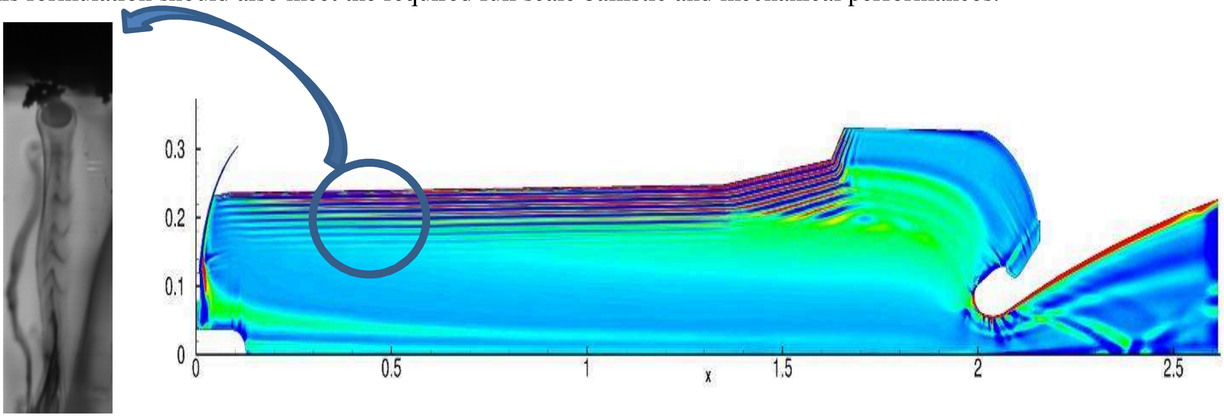


Figure 5: Aluminium combustion close to propellant burning surface- Experimental characterizations bench test bench and numerical effects modelled in the SRM combustion chamber (rotational field)

Thanks to the "Velocity Coupled T Burner" (VCTB) experimental test bench, initially proposed by M. Beckstead (Cf [Ref. 11], [Ref. 12] and [Ref. 13]) and adapted for our own need at HKS, the destabilizing role of aluminium combustion has been demonstrated, proved and studied. Several aluminized propellant formulations have been tested in order to quantify Al combustion contribution to the SRM unsteady behaviour (cf Figure 6).

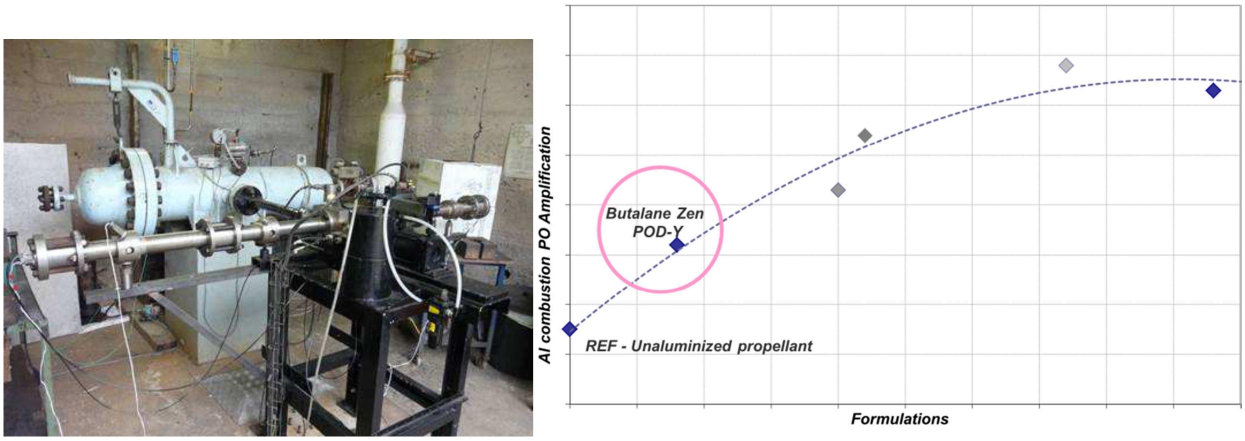


Figure 6: Results of Velocity Coupled T Burner – Al combustion contribution measure to PO amplification

Thanks to these tests, a propellant classification and ranking was available and a Butalane® Zen propellant formulation, helpful to avoid in a large part the effect of Al combustion, was defined. This formulation was finally proposed to be tested at the end of 2014 in accordance with the preliminary design studies of Ariane 6 program.

2.2 Concepts validation

To validate proposed solutions, a demonstrator SRM has been designed at a higher representative scale. This demonstrator represents the last scale of study, before the full one.

If the main objective of the firing test is the validation of design choices both in terms of geometry and propellant formulation in order to reduce risks of pressure oscillations occurrence in large aft-end finocyl SRM, this test was expected as a qualification of POD-Y demonstrator as an experimental tool for A6 development requirements.

The demonstrator SRM was named POD-Y and has been conceived at a representative scale, especially for Al combustion effects which are scale dependent.

The global demonstrator design presents:

- Metallic heavy wall cylinder and domes (derived from another demonstrator named POD-X)
- Thick internal insulation using A5 MPS GSM55 rubber
- Finocyl-type grain with a Butalane® Zen formulation for this scale
- Specific igniter derived from existing hardware
- Simplified fixed nozzle adapted to the chosen scale
- Heavy instrumentation, mainly focused on dynamic pressure measurements

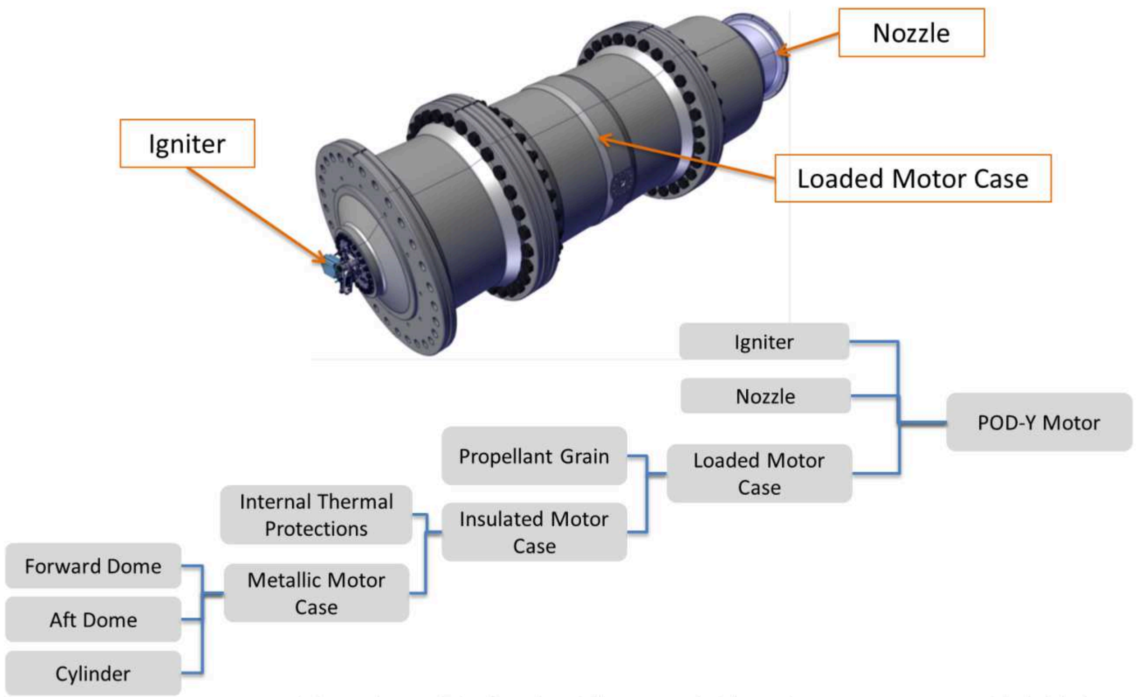
Its development benefits from the POD-X ESA Program by using similar metallic parts. Based on developed tools and means, and existing metallic POD-X motor case, it was verified and validated that the POD-Y proposed subscale 2/11th demonstrator could be representative of A6 SRM full scale pressure oscillations phenomenon.

Demonstrator development has been done by always keeping in mind that each part must satisfy a good relevance of pressure oscillations phenomenon. This means that for the modification of each driving parameters needed a specific study and expertise to determine the potential impact on the demonstration objectives.

To grow in scale, the initial combustion chamber geometry is similar to the one tested on previous small experimental mock-up. The full scale is all the better reproduced in the demonstrator as some geometrical details could be included and that couldn't at the smaller one. As a consequence, POD-Y geometry could be considered as a good representation of the full scale one.

The nozzle throat erosion was specially studied in detail in order to preserve a good relevance in term of Klemmung evolution with operation time.

Previous studies underlined the importance to focus on the beginning of the firing test in terms of pressure oscillations occurrence. This aspect was taken into account and the igniter was dimensioned to have a representative SRM pressurization.



Characteristics	Values
Length (m)	2.8
Mass (t)	3.6
Metallic case external diameter (mm)	745
Propellant mass (t)	1.1
Throat diameter (mm)	106.9
Exit cone diameter (mm)	488

Figure 7: POD-Y Production cycle and main characteristics

The SRM grain was casted in HKS site in Gironde and the demonstrator was then assembly and fired in DGA-EM site.

Before the firing test, many fine computations were necessary to predict the steady and unsteady POD-Y behavior. The compilation of theoretical know-how, the set of experimental data and numerical tools acquired all along this program, were necessary to predict:

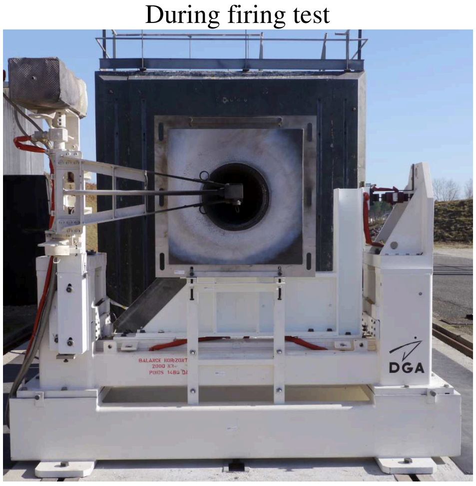
- The global steady pressure evolution with time
- The global unsteady scenario both in terms of phenomenon, pressure amplitudes and frequencies evolution with operating time.

Before firing, a complete scenario for the unsteady behavior was consequently described, based on HKS methodology. According with this scenario, predictions were:

- The possibility of a very quick PO due to hydrodynamic instability in the very first times of operation, on 1L mode, and levels about 100mbar;
- A probable weak PO between the interval [3s-7s] on 1L mode, about 30mbar levels;
- Stability during the rest of the fire with a possible instability during tail-off but very difficult to predict.

Before firing test

During firing test



After firing test

Figure 8: POD-Y Bench firing test (Source DGA-EM)

The bench firing test took place in March 2015 in “DGA Essais de Missiles Facilities”, in Saint Jean d’Illac near Bordeaux on a horizontal test bench.

A first assessment of the results exploitation is presented on next figures, in which predictions, pressure and mean results of P80 SRM’ fires (envelop of burst peaks) are reported.

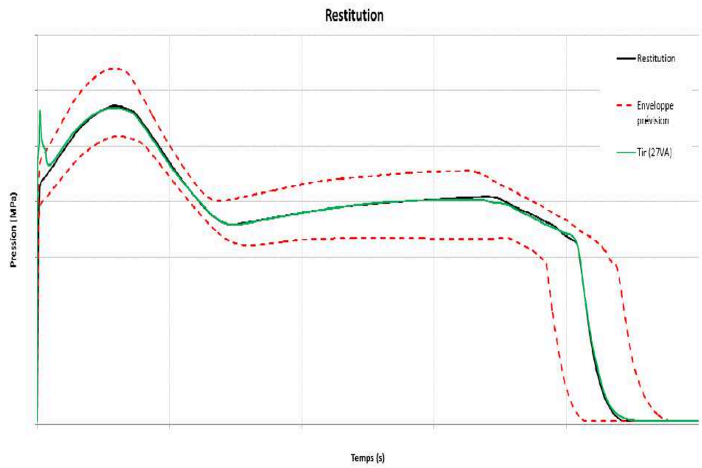
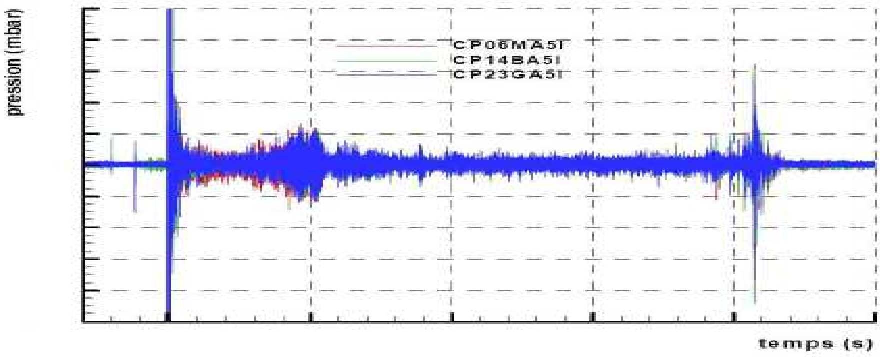


Figure 9: Pressure curve – Comparison between prediction & results of POD-Y Bench firing test

The steady behavior results were in really good accordance with previsions. This first success was important because instabilities are expressed as pressure fluctuations around the average pressure value dependant on the steady-state operating point.



Unsteady pressure result (ONERA exploitations)

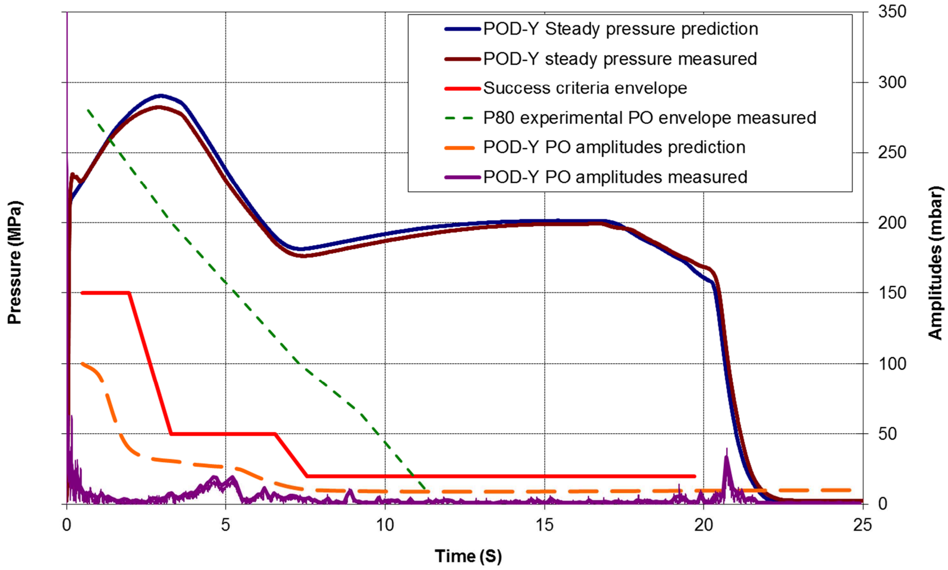


Figure 10: Unsteady pressure results – Comparison between prediction & results of POD-Y Bench firing test

The pressure instabilities were observed with dedicated specific measurements to have a good precision (<10mbar). The unsteady behavior exploitation is presented on Figure 10. As foreseen, unsteady pressure levels are very low all along the firing test, and less than 50 mbar. The measured phenomena were well predicted by computation and correspond to very weak hydrodynamics instabilities linked to SVS.

By comparison with VEGA P80 SRM ([Ref. 14), which geometry is quite close from POD-Y one, we see on the same figure that the aim of reducing PO level is reached.

The success of this firing test demonstrates that it is possible to conceive *a priori* a stable SRM and to do this, choosing the good propellant formulation is of very high importance.
Beyond the SRM geometry, the HTPB Butalane® Zen evaluated in a demonstrator motor assesses the capability to reduce (up to suppress) ITHAC phenomena with a suitable propellant formulation.

Propellant design rules to fulfil these two criteria are now known from demonstration program results.

4. Conclusions

Numerous physical phenomena that contribute to the formation of pressure oscillations can appear during the SRM operation. Since the frequencies associated with these instabilities can couple with the launcher's structural modes, these oscillations must be mastered. For these reasons, HKS has conducted extensive studies to improve pressure oscillation understanding in solid rocket motors. The resulting experience and expertise acquired have led to develop a specific methodology that addresses the problem of PO for a large number of motor configurations.

Today, a dedicated PO program led us to mature technologies that can offer practical solutions for drastically reducing amplitudes for future A6 SRM. The full validations were obtained through a middle scale but representative demonstration built after a compilation of all the theoretical, numerical and experimental know-how. The stable fire of a demonstrator POD-y specifically designed in this aim shows that HKS has reach a certain maturity to master PO problems.

The success of this demonstration test is an important milestone that highlights the possibility to design *a priori* a P120C solid rocket motor for VEGA-C and Ariane 6 with limited pressure oscillations.

4. Acknowledgements

We would like to thank CNES and ESA for their collaboration and contribution, and ONERA and DGA-EM for their test facilities and associated analysis.
Members of IDC program are also acknowledged for their contribution to this successful demonstrator firing.

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