Numerical investigation on hot gas valve system couplings

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ABSTRACT

In this paper, a simplified configuration of a hot gas valve system has been computed using the CFD code named MSD (ONERA). The pressure feedback loop of the active control device and the resulting fluid mesh deformation have been implemented as user routines. Results of the simulation are compared to experimental data in terms of chamber pressure and pintle displacement. A good global agrement is obtained. One focuses also on the acoustics generated inside the motor.

INTRODUCTION

Thrust control with valves remains a challenging technical issue and requires high level performances ([1] and [2]). The development of new efficient technologies for hot gas valve systems such as Divert and Attitude Control Systems (DACS) (Figure 1) for Kill Vehicle is one of Ballistic Missile Defense major interests ([3] and [4]). Figure 2 presents the global principle structure of a valve. To improve the optimization of such systems, a better understanding of all relevant physical phenomena is required. Computational simulation is one pertinent method to treat this important issue.

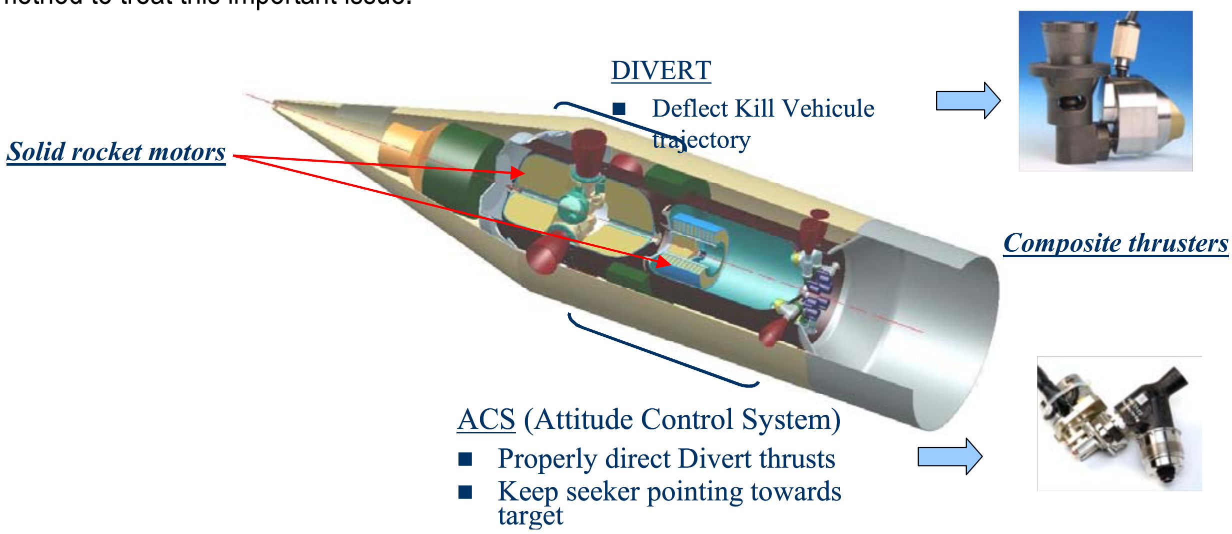

Figure 1 : Solid DACS design for Kill Vehicle.

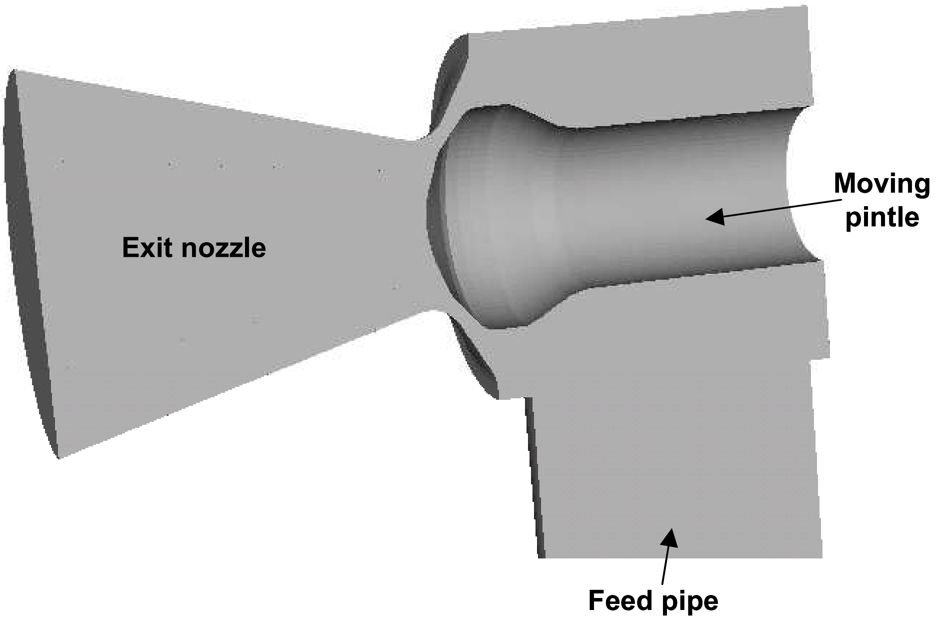

Figure 2 : valve's principle structure.

To deal with this kind of numerical analysis, one has to take into account numerous different physical phenomena concerning hot gas valve systems:

- ✓ high dynamic response of active control device (pintle actuated through a pressure control loop)
- ✓ propellant combustion,
- ✓ combustion chamber acoustics,
- ✓ structures mechanical behavior,
- ✓ …

and their potential couplings. Such a complex simulation in an industrial configuration is a very challenging issue.

The long-term objective of such an approach is to improve the CFD readiness level to later optimize such hot gaz valve system with pressure regulation and so to enhance the optimization of the entire valve system, especially on the following items:

- ✓ aerodynamic inner profiles,
- ✓ mechanical design (with dynamic effects),
- ✓ unsteady combustion,
- ✓ ignition,
- ✓ pintle actuation,
- ✓ SRM pressure control loop.

This paper presents an instationnary computation of a simplified configuration of a hot valve system which was performed using the CFD code named MSD (ONERA). First, the strategy used to perform an accurate fluid mesh deformation, then the way the pressure feedback loop of the active control device was implemented will be presented. After that, the comparaison between simulation results and the experimental data in terms of chamber pressure and pintle displacement will be performed. Finally, one focuses on the acoustics generated inside the motor.

FLUID MESH DEFORMATION

Keeping a good mesh quality during all the duration of the calculation, despite the displacement of the pintle, is one of the major challenges of such a simulation. With the CFD code MSD, that requires structured meshes, one can use three methods to deforme the mesh.

The first two ones are automatic: they move the inner nodes of the mesh depending on the prescribed displacement of the nodes belonging to the boundaries.

Those two methods differ by the laws that are used to move the inner nodes:

- ✓ The first one uses the lines of nodes of the structured mesh to calculate the displacement of the nodes.
- ✓ The second one uses local springs linking a node with his neighboors and resolve the linear system so formed to find the displacement of each node.

Those methods are accurate when the boudaries moves and deformes themselves, but in valves systems one only focuses on rigid bodies movements. So, in order to master more precisely the mesh quality during the whole calculation, an another method is used: interpolation between meshes prepared before.

The principle is quite simple but only usable for rigid body movement. One makes several meshes, with different positions of the pintle that are surrounding those that will be reached during the simulation. Then, at every time step of the calculation, the place of the pintle is known and the adequat mesh is obtained by interpolation of the two meshes which positions of the pintle are closely framing the one wanted.
Moreover, MSD needs structured meshes and those are really well designed to perform such an interpolation. The picture on the middle of Figure 3 shows the result of the interpolation of the meshes of the two other pictures. One sees that the cells remain of good quality, thanks to the displacements of the nodes along the boundaries that are easy to perform with this method.

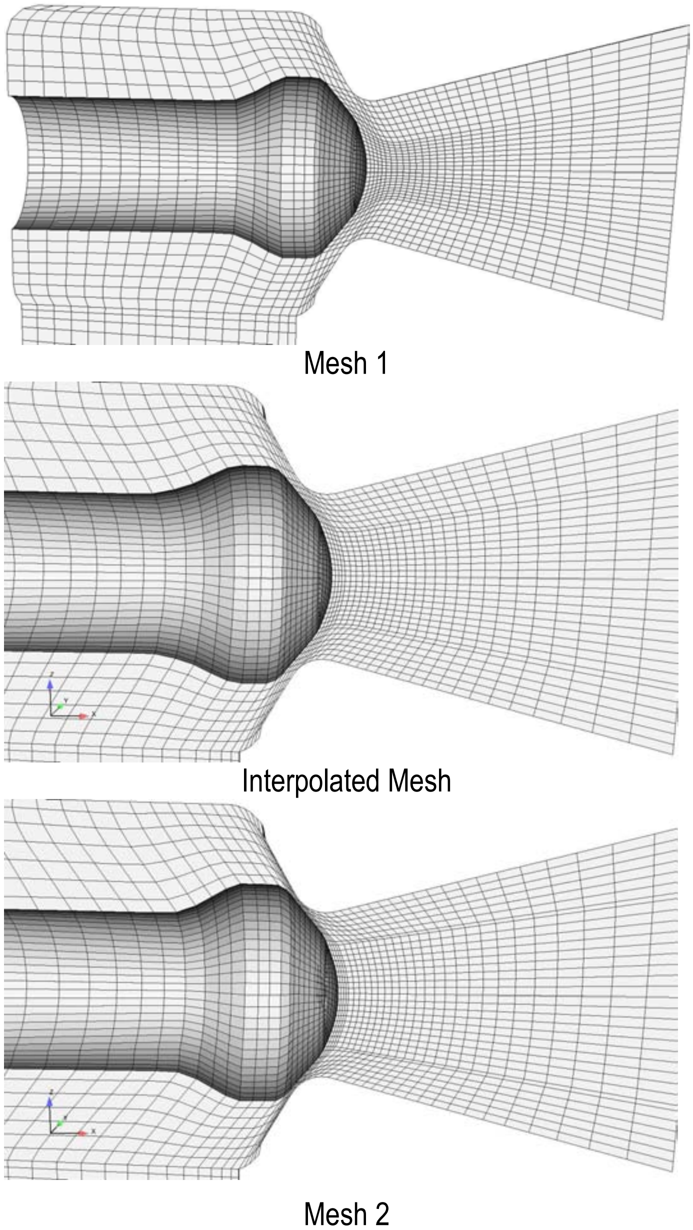

Figure 3 : interpolated mesh between mesh 1 and mesh 2.

THE FEEDBACK LOOP OF THE ACTIVE CONTROL DEVICE

The displacement of the pintle is computed via a specific control algorithm in order to reach a prescribed chamber pressure. The principle of this algorithm is the following (Figure 4):

- ✓ Chamber pressure is measured
- ✓ The pressure order is known at this moment
- ✓ The difference of pressure is translated in a certain sonic area to be reached via an integro-differential law
- ✓ Knowing the relation between sonic area and pintle position, the displacement to impose is so determined.

All the specificity and complexity of such an algorithm remains in the integro-differential law used and in all the corrections that are done to take into account specific phenomenons as the ignition of the propellant or the dilatation of some pieces of the valves…
This algorithm was implemented as a subroutine in MSD. Its entries are the chamber pressure measured and the specified pressure to reach. Its exit is the displacement (or the position) of the pintle, computed as presented before.

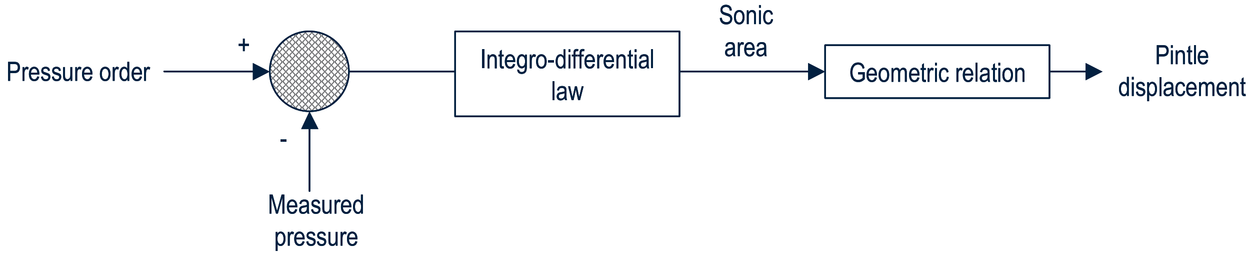

Figure 4 : principle of the control algorithm.

APPLICATION TO THE SIMULATION OF A VALVE'S HOT FIRE TEST

PRESENTATION OF THE EXPERIMENTAL DEVICE AND RESULTS

As presented on Figure 5; the device was composed of a combustion chamber with a discharge nozzle and a pipe linking the chamber to the valve.

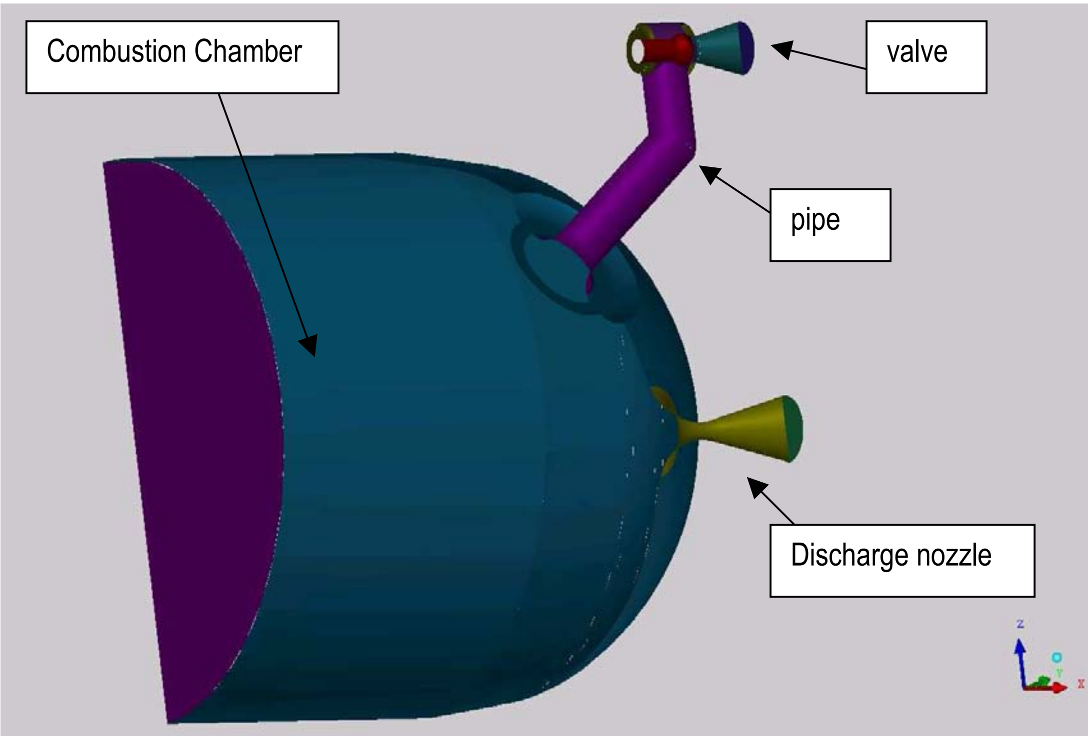

Figure 5 : Design of the experimental device.

One only focuses on what happened during the beginning of the firing test. The valves is initially closed. As shown on Figure 6, the pressure order was imposed since the beginning of the test. So, after the ignition and the end of the ignition device working, at t1, the pintle began to move at t2 in order to stabilize the pressure elevation at the prescribed level. It has to be noticed that it takes about the half of the considered interval of time to reach the thermal equilibrium of the whole experimental device.

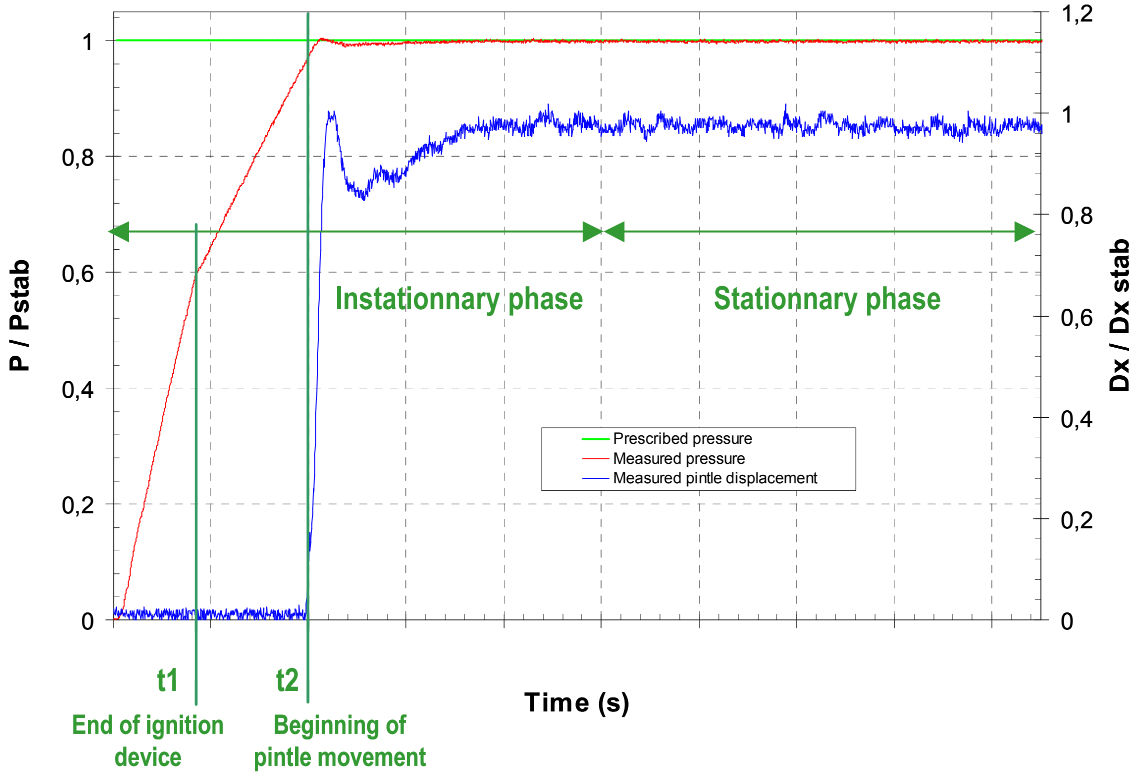

Figure 6 : Experimental results in term of chamber pressure and pintle displacement.

COMPUTATIONNAL RESULTS

The main problem we had to face to compute this test is that the pintle is closed at the beginning of the test. With MSD, it is not possible to simulate the opening of the valve, because we cannot create mesh cells. So, a meshing configuration as closed as possible was made, and it was used at the beginning of the calculation. Combustion gas properties as representative as possible of the experimental configuration was used. Following data were used as boundary conditions:

- ✓ wall temperature, computed with a thermo-mechanical calculation
- ✓ entrance flow rate that is known via the combustion speed of the propellant, itself depending on the chamber pressure.

The calculation began with a pressure ratio of 0.9, that was arbitrary decided to be higher than the one at the end of the ignition device operation and lower than the one of the pintle displacement beginning. The pressure ratio order was fixed at 1 since the beginning of the calculation.

The result of the simulation is presented on Figure 7, on the left the evolution of the chamber pressure and the one of the pintle displacement on the right. The initial instant of those graphics is the beginning of the pintle displacement in each case.
The static pressure ratio reached by the calculation is 1.002 so the pressure ratio order (1.0) is well respected. The instationnary phase is nevertheless not so close to the experimental result. The global pressure increase in the calculation is quite good but the overshoot phenomenon (during the beginning of the movement) is not modelised.
The displacement ratio of the pintle stabilizes at about 1.03 instead of 1.0 in the experiment. The difference is surely due to the thermic equilibrium that is not yet reached and a lack of knowledge concerning the evaluation of the entrance flow rate and so to the chamber pressure. The overshoot phenomenon is there neither well reproducted. The main hypothesis to explain this is that the calculation does not begin with a closed valve. The algorithm of the feedbackloop is an integro-differential one, so the chronology of the chamber pressure is very important but not accurate in our calculation compared to the experiment. Unfortunately, it is not possible to perform such a simulation (valve closed at the beginning) with this methodology. A comparison with another

firing test that has a changing pressure order but not with an initial closed valve will be soon evaluated to validate our simulation mean.

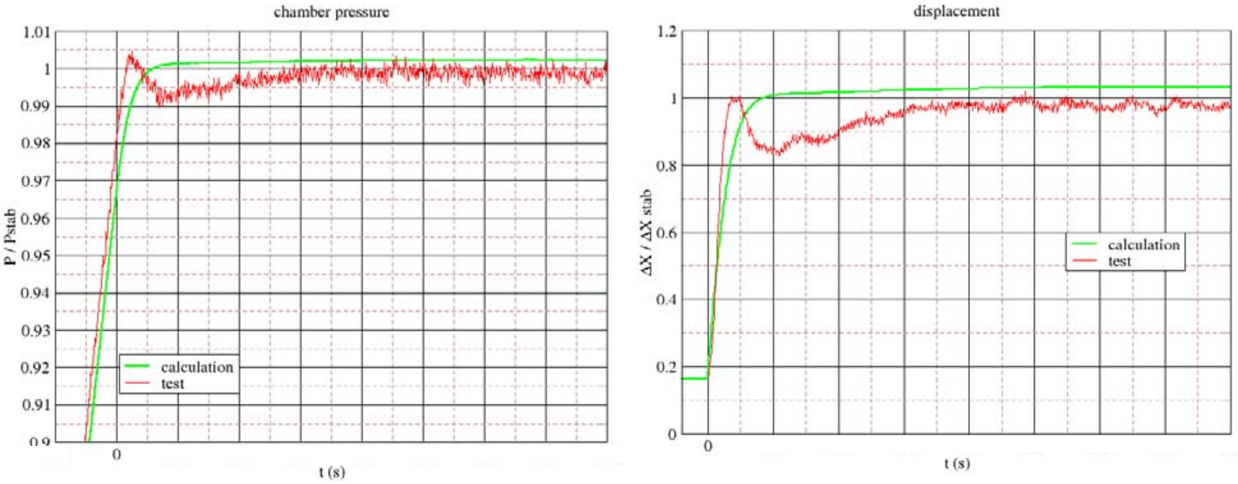

Figure 7 : Time evolution. Left: chamber pressure. Right: pintle displacement.

ACOUSTICS IN THE CHAMBER

One of the purpose of this study is to investigate the potential coupling between the pintle displacement and some pressure instabilities such as acoustics waves generated into the chamber. In order to search some instabilities, a spectral analysis was performed on the pressure signal. The analysis consists on an "tridimensionnal" Shock Response Spectrum (SRS3D) that is a SRS analysis for each Hertz between 1 and 5000Hz on temporal sliding windows of 0.05s width with a time step of 0.01s of the initial signal. This type of analysis is more accurate in this case than a classical FFT because it allows not to pollute the Fourrier transform with low frequencies coming from the global evolution of the pressure. So we have a more precise evaluation of potential predominant high frequencies, which one is looking for, the frequency of the first acoustic longitudinal mode of the chamber being around 1400Hz.

The result of the treatment of the experimental pressure evolution is shown on Figure 8. No scale is indicated for the levels of response because they have no physical meaning. No particular frequency is revealed, that means that no particular instationnary pressure phenomena were present during the firing test.

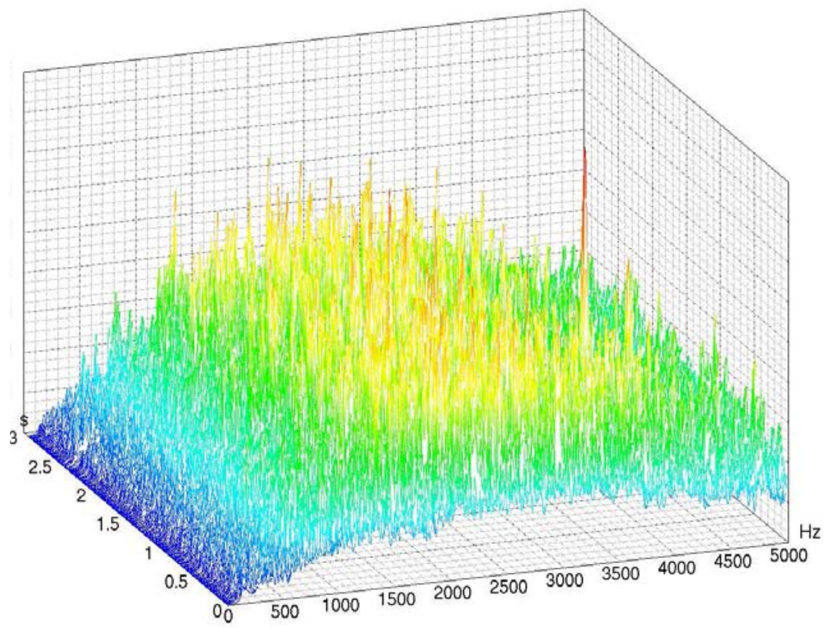

Figure 8 : SRS3D of the experimental pressure signal.

The result of the analysis of the calculated pressure is shown on Figure 9. A principal frequency is predominant: around 1350Hz, which is close to the one of the first acoustic mode. The amplitude of this mode is rapidly decreasing after the beginning of the pintle movement. Its maximum decreases by a hundred factor in 0.1s after the beginning of the pintle displacement.
So, as in the experiment, one can say that no relevant acoustic phenomenon is highlighted by the simulation.

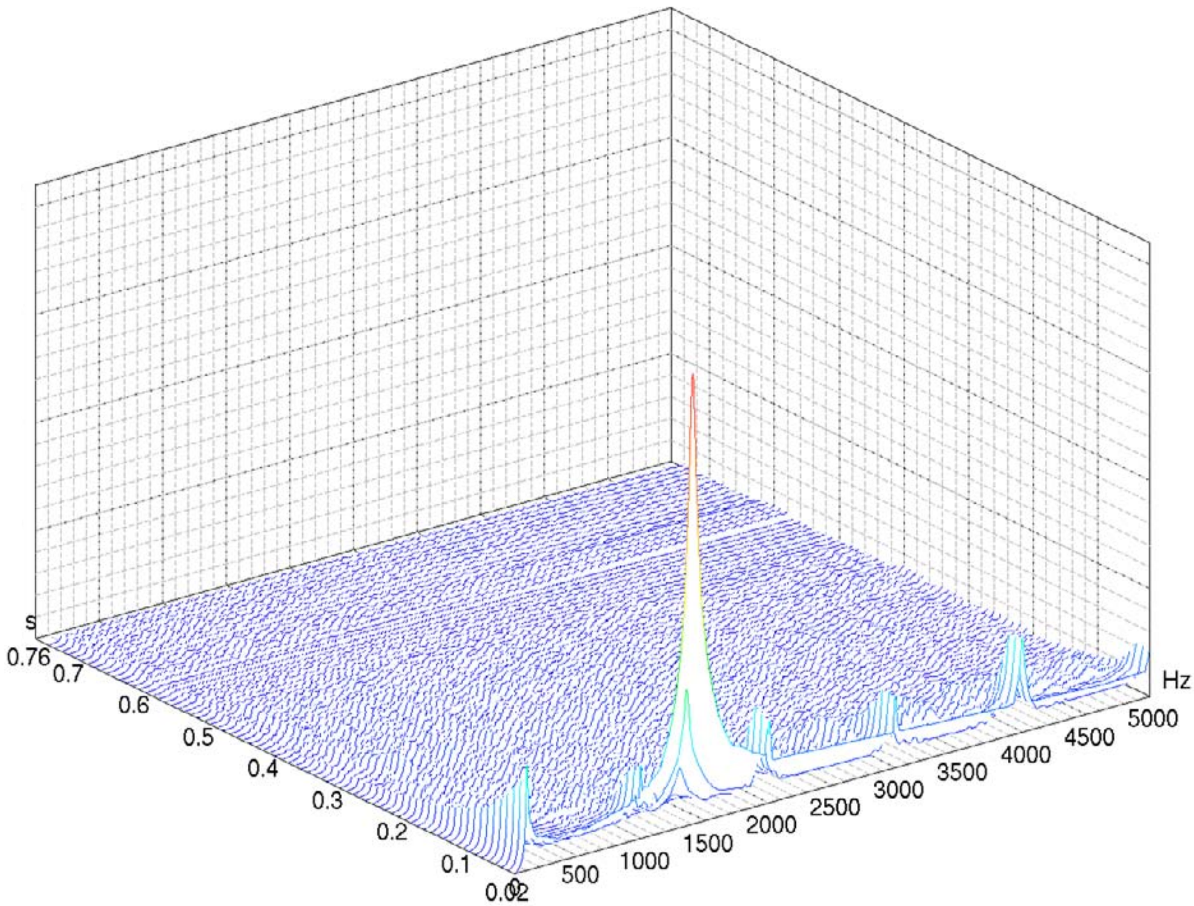

Figure 9 : SRS3D of the calculated pressure evolution

CONCLUSION

An accurate technic of mesh deformation and the pressure feedback loop of the active control device were implemented in the CFD code MSD (ONERA). It allowed to perform an instationnary simulation of a valve's hot fire test.
A good agreement between experiment and calculation in terms of global evolution of the chamber pressure and pintle displacement was obtained. Some differences remain on the fine evolution of those quantities but the reason of such differencies are identified. Additional hot firing tests will be analysed to validate the calculation methodology without the particularities as ignition, initially closed valve or thermic non-equilibirum.
This methodology now allows us to investigate more precisely potential acoustic phenomena in the combustion chamber and a potential coupling between the pressure control loop and the chamber acoustics.
The future improvement of this work will be the introduction of new laws of propellant combustion in order to investigate potential combustion instabilities due to the pintle displacement and the coupling between combustion, acoustics and the pressure control loop.

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