NUMERICAL SIMULATION OF PRESSURE OSCILLATIONS IN SOLID ROCKET MOTORS

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Periodic vortex shedding as a source of acoustic oscillations in SRM has attracted the attention of several researchers during the last decades. The reason of this interest is an unpredicted oscillatory behavior observed in several motors during combustion. Often the presence of complex propellant grain geometry, such as in segmented motors, has been indicate as a strong reason for the presence of such oscillations. On the other hand, the continuous request from the launcher industry of ever higher thrusts is leading to the development of large solid propellant motors, which, for technological reasons must be segmented. In segmented SRM different types of Ethylene Propylene Diene Monomer (EPDM) based rubbers are often used to prevent the combustion of the frontal face of propellant grain segments. During flight, the inert material burns at a slower rate than the propellant, leading to annular ring protrusions that act as an obstacle to the flow in the combustion chamber. The flow past these rings produces regions of high shear and causes periodic vortex shedding that can interact with the acoustics of the combustion chamber producing amplification of pressure fluctuations.

Oscillatory behavior has been observed in Space Shuttle RSRM (Re-designed SRM), in the Titan IV SRMU (SRM Upgrade) and more recently in the Ariane 5 P230 [1, 2]. For Space Shuttle RSRM and Ariane 5 P230 booster, these oscillations have been attributed to a periodic vortex shedding due to the presence of frontal thermal protections (PTF). When the vortex-shedding frequency is the same as the natural frequency of the chamber, pressure oscillations reach a maximum. Pressure oscillations cause thrust oscillations which, in their turn, lead to critical dynamic loads on the payloads. This can reduce the overall performances and usability of the launcher. Several experimental and numerical studies in cold–flow [3, 4] have demonstrated the role of the thermal protection in this process. In these experiments, the vortex shedding is produced by the obstacle and pressure oscillations reach large magnitude when the vortex shedding frequency is close to the frequency of one acoustic mode of the duct.

The basic mechanism of this process can be described as a feedback loop consisting of the following steps:

- the hydrodynamic instability of the shear layer region that develops near a sudden expansion of the geometric configuration (such as the thermal protection);
- the roll – up and advection of a vortex structure;
- the impingement of the vortex on a surface located downstream (such as the nozzle head);
- acoustic propagation from the downstream source;
- the acoustical triggering and generation of a new vortex structure.

Numerical simulation of such complex phenomenon is quite a challenging task. In the past several author have presented numerical results on pressure oscillations in SRM showing in many cases quite important differences with experimental data [5, 6].

In a previous paper Anthoine et al. [7] conducted an experimental study of pressure oscillations in a small scale device with *cold flow*, presenting reference data for pressure oscillations in such scaled device. In their paper Anthoine et al. [7] presented also some comparison with numerical results. Comparison with experimental tests shows that globally the frequencies are well simulated by numerical codes despite pressure oscillation levels are largely overestimated. Oscillation levels obtained from the numerical simulations were one order of magnitude larger than the experimental ones. Unfortunately very often numerical results fail in the prediction of amplitude of pressure oscillation. It is opinion of the authors of the present paper that pressure oscillation are basically a fluid dynamic phenomenon and therefore it can be adequately reproduced using a pure CFD approach. Moreover, other goal of the present paper is to evaluate the possibility of the use of a commercial CFD package for the estimation of pressure oscillation frequencies and amplitudes in Solid Rocket Motors.

Validation of the adopted approach will be conducted on the base of the cold flow test case of Anthoine et al. [7]. As intermediate step a numerical simulation on a class of subscale SRM (LP6) [8] is presented. Finally an application to pressure oscillations in Ariane 5 MPS P230 boosters will be discussed. Results are compared with available experimental data.

Mathematical modelling

Focus of the present paper is the study of the evolution of vortex structures, responsible of pressure oscillations. Therefore the most important zone to study is located between the PTF and the nozzle head of SRM. For this reason, it is possible to describe the physical domain as a long circular duct with a submerged nozzle placed at one end. A large cavity is present near the inlet section of the nozzle. An obstacle (PTF) in the form of one annular ring is placed inside the duct upstream of the nozzle (Fig. 1). Anyhow in order to maintain the correct acoustical properties of the motor, during numerical simulations the whole length of the combustion chamber has been considered. Flow field has been assumed axial-symmetric.

Since three different cases will be studied, only the geometry of the first case (so-called cold flow) is represented in Fig.1, with inflow parallel to the duct axis. For the other two cases, in which a scaled and a real scale SRM are simulated, inlet conditions are imposed normally to side walls, simulating inlet due to solid propellant combustion. Geometrical scale is quite variable between the three cases, ranging from 0.40m of the cold flow case up to 24.5m corresponding to the full scale combustion chamber of P230 motor.

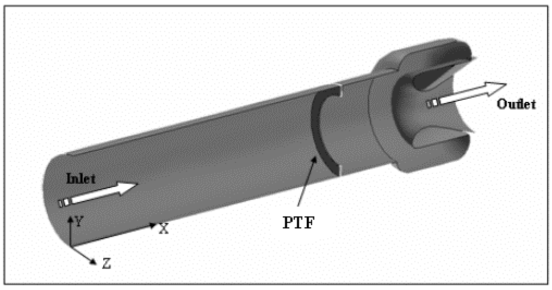

Fig. 1. Physical problem.
(cold flow test case).

All the numerical simulations have been conducted by means of a standard CFD package based on control–volume technique.

Data monitoring

Data monitoring is a very delicate issue for obtaining a good estimation in terms of spectrum frequencies and amplitudes. Due to the complexity of the phenomenon under study, a long initial transient has been simulated. In this initial phase, the mechanism of feedback is built-up in the computational domain. After this initial transient, the data acquisition is started.

Application to a cold flow test case

In this section, to validate the adopted approach, an application to a cold flow test case is presented. Results are compared with those found experimentally and numerically by Anthoine et al. [7].

During numerical simulations static pressure has been acquired at different control points placed in the computational domain. In particular, one of these points has been chosen near the inlet section to match the sampling point used by Anthoine et al. [7]. All the results presented are based on data acquisition at this point.

Firstly a validation of numerical results has been conducted by means of a mesh sensitivity analysis. Four different computational meshes have been employed for grid validation, ranging from 3,950 (mesh M0) up to 44,800 mesh points (mesh M3). Comparison has been conducted considering the most excited frequencies and their amplitude P_{RMS}/P_{Mean}.

From the comparison of the frequency and amplitude values (Tables 1 and 2) obtained with successive mesh refinements, it is results that mesh M2 is sufficiently accurate to reproduce pressure oscillations behaviour. In fact it is worthy to observe that for the first peak, the most important from an engineering point of view, mesh M2 and M3 give a difference of 0.5% in the frequency values and a difference of 2.3% on the amplitude (P_{RMS}/P_{Mean}). On the basis of these results mesh M2 has been chosen for the numerical simulations presented in this section.

Numerical results have been also compared with published experimental and numerical data [7]. A quantitative comparison of the frequency peaks and their relative pressure amplitude is given in Table 3 and Table 4. The first, and usually most important peak, is at 402 Hz and differs by about 2% from the experimental one at 410 Hz. Very good agreement is also obtained for the frequencies of the other peaks. It is worthy to remark that these frequencies were not explicitly reported in [7] but have been extracted from the graphical data presented in their paper. The computed frequency values obtained by Anthoine et al. [7] are in good agreement with their experimental results (Table 3). However this is not the case for the relative pressure fluctuations in which the numerical predictions of Anthoine et al. [7] were in error by an order of magnitude with respect to experimental results as may be seen in Table 4. On the contrary, in the present work there is a remarkably good agreement between the numerical results, obtained for the relative pressure fluctuation, and the experimental ones presented in [7] (Table 4). In fact, a comparison of the relative pressure fluctuations at the frequencies of first four modes with experimental results [7] (Table 4) shows that in correspondence of the first mode, at 410 Hz, the present numerical results overestimate, by about 13%, the experimental ones. This difference decreases to 11% using data obtained mesh M3. Since the differences between the numerical and the experimental data are small, the present results indicate that the flow is adequately described by an axial-symmetric model. Thus, the suggestion [7] that three-dimensional effects were responsible for poor numerical predictions in evaluating the magnitude of the pressure fluctuations is not correct.

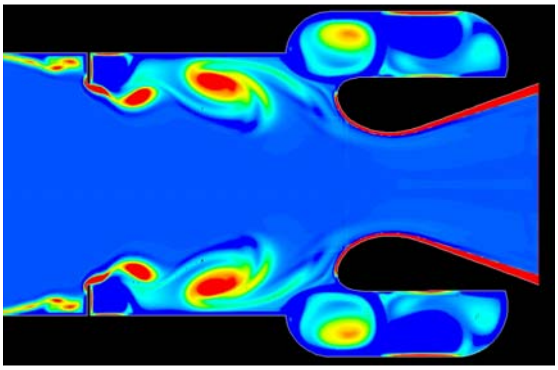

Fig. 2. Configuration of vorticity structures (cold flow test case).

Table 1

Comparison of the frequency peaks: mesh sensitivity analysis (cold flow test case).

Mesh	**I° Mode (Hz)**	**II° Mode (Hz)**	**III° Mode (Hz)**	**IV° Mode (Hz)**
M0	425	850	1298	1720
M1	410	899	1342	1799
M2	402	891	1337	1767
M3	400	885	1329	1758

Table 2

Comparison of P_{RMS} / P_{Mean} amplitude: mesh sensitivity analysis (cold flow test case).

Mesh	**I° Mode ($\times 10^{-3}$)**	**II° Mode ($\times 10^{-4}$)**	**III° Mode ($\times 10^{-4}$)**	**IV° Mode ($\times 10^{-4}$)**
M0	4.25	6.12	1.81	0.36
M1	1.74	4.80	2.85	1.24
M2	1.28	10.1	7.10	3.32
M3	1.25	9.98	6.47	3.29

Table 3

Comparison of the obtained frequencies with the experimental data [7] (cold flow test case).

Mode	**Present (Hz)**	**Exp.[7] (Hz)**	**Num. [7] (Hz)**
I	402	≈ 410	410
II	891	≈ 875	840
III	1337	≈1280	1270
IV	1767	≈1740	1725

Table 4

Comparison of P_{RMS}/P_{Mean} amplitude in correspondence of the first 4 peaks. (cold flow test case).

Mode	**Present ($\times 10^{-3}$)**	**Exp. [7] ($\times 10^{-3}$)**	**Num. [7] ($\times 10^{-3}$)**
I	1.28	≈1.13	≈13.00
II	1.01	≈0.95	≈ 4.00
III	0.71	≈0.17	≈ 1.75
IV	0.33	≈0.10	≈ 2.25

Application to small scale SRM (LP6)

In this section a numerical study of pressure oscillations has been performed on a class of subscale solid rocket motors called LP6. This test case represents Ariane 5 booster in scale 1:15 and constitutes an intermediate step between a cold flow test case, discussed in the previous section, and the full scale configuration of solid rocket motor.

All geometrical data have been deduced by ONERA technical note relevant to LP6 test called ARTA01/03 financed by CNES in the frame of ARTA 3 program [8]. Due to the unavailability of all data, especially the combustion gas characteristics, some data have been hypothesized and calculated by AVIO. Combustion time t=8s has been simulated.

Data of experimental firing tests, have been used in order to qualify the numerical results both in terms of frequency values and in terms of pressure oscillations magnitude. During the numerical simulations control points are located in correspondence of the motor head. In these points the static pressure has been sampled.

Obtained results show a pronounced mode at 316 Hz with amplitude of 1631 Pa. This value is in good agreement with experimental data, showing a difference lower than 9%.

Figure 3 shows large vorticity structures during the evolution from the PTF to nozzle head.

Application to MPS P230 pressure oscillation

As final step of this work a numerical simulation of pressure oscillations in a full scale motor has been performed. To conduct this analysis the flow and geometrical conditions relevant to “second peak” of Ariane 5 MPS P230 has been chosen. Since the PTF has an axial-symmetric geometrical configuration, during the simulations axial-symmetric flow conditions have been assumed. In order to reproduce the real deformed geometry assumed by the PTF and so the real flow conditions in the combustion chamber a preliminary coupled Fluid Structure (FSI) analysis has been conducted.

Details of the approached adopted are presented in [9]. On the basis of the deformed geometry of the eroded PTF obtained from FSI analysis, unsteady CFD simulations have been started maintaining the shape of PTF frozen in that configuration.

During the numerical simulations control points are located in correspondence of the motor head and in these points the static pressure has been sampled.

In order to have some sensibility on dependence of results from the computational mesh, three different meshes have been adopted, ranging from 100,000 (mesh A) to 400,000 (mesh B), up to 1,200,000 (mesh C) mesh points. All results (mesh A, B and C) present the main peak at 20.7 Hz that is also in good agreement with the values measured during the firing test and/or obtained from flight data (at almost 21.2 Hz). It is worthy to observe that

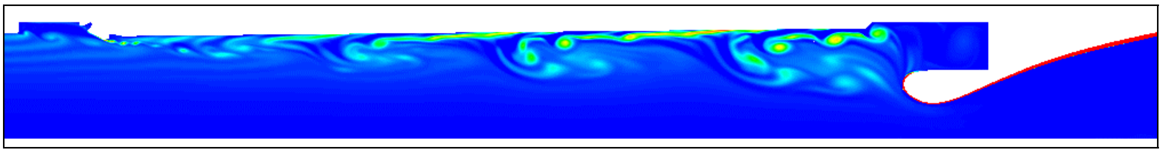

Fig. 3. Flow visualizations during the evolution of a large vorticity structure (LP6).

experimental frequency is inside the error bar of numerical simulation. This first result shows the capability of the method to predict oscillation frequencies also with the coarser mesh (mesh A).

On the contrary the amplitude of oscillations changes quite largely going from 40 mbar (mesh A) to 149 mbar (mesh B) showing the need of an important effort on mesh sensitivity analysis whenever amplitude of oscillations is a result of interest. The amplitude of oscillations obtained using mesh B (149 mbar) is very close to the one obtained with mesh C (151 mbar) showing that the numerical solution has reached an asymptotic value. A picture of results in terms of frequencies of oscillations and their amplitudes is reported in Figure 4. Therefore mesh B has been selected as the best compromise in terms of costs/performances for further analysis.

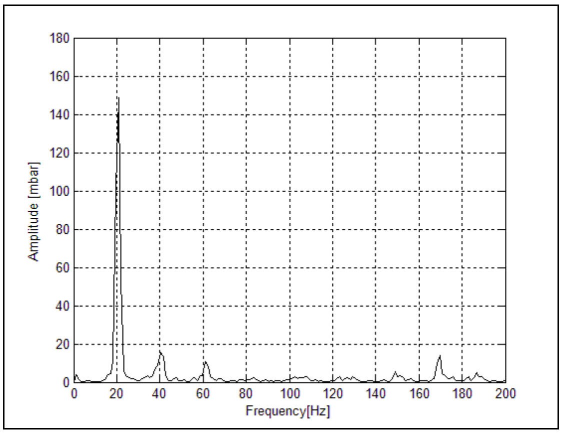

Fig. 4. Pressure spectrum obtained with mesh B (P230).

Finally, in Fig. 5 a qualitative comparison of the different flow structures obtained with the three meshes is presented. It is possible to observe, that the differences in terms of flow structures between mesh A and mesh B are clearly visible; on the contrary differences between mesh B and mesh C are not significative, also considering that it is not possible to produce flow visualizations with exactly the same conditions.

Obtained results have been compared in terms of pressure oscillation amplitude, with available experimental data obtained from bench/flight data of P230 booster. Comparison has been conducted on the basis of energy in the frequency band 17-25Hz, showing a difference from averaged flight data lower than 5%.

It is worthy to observe that all the mechanisms of the vorticity production in SRM have been observed and properly reproduced:

a) obstacle vortex shedding: vortices born from the tip of PTF;
b) parietal vortex shedding: vortices born from the propellant surface;
c) angle vortex shedding: vortices born from the propellant angle in the aft part of segment grain.

The three mechanisms of vortex shedding are clearly visible in Figure 6. Due to the complex evolution of vortex structures in the combustion chamber of SRM, the evaluation of quantities of engineering interest such as the number and the velocity of vortices is not a trivial work. Vortices, initially produced from the shear layer on the PTF, are merged in the initial phase of the process and then mixed with the vorticity structures extracted from the side (propellant) walls. This gives to the all phenomenon a very complex behavior (Fig. 6). In spite of these complexities, it is possible to continue to utilize these genuinely intuitive quantities. Vortices convection velocity can be assessed by means of the evaluation of the time needed to a single large flow structure to travel from the detachment point (PTF) to the impact surface (the nozzle head). The number of vortices can be conventionally defined as the number of large scale structures observed in nozzle proximity since the production of a single large flow structure to its impingement on the nozzle head. Figure 7 shows the complete sequence of the evolution of a large vorticity structure.

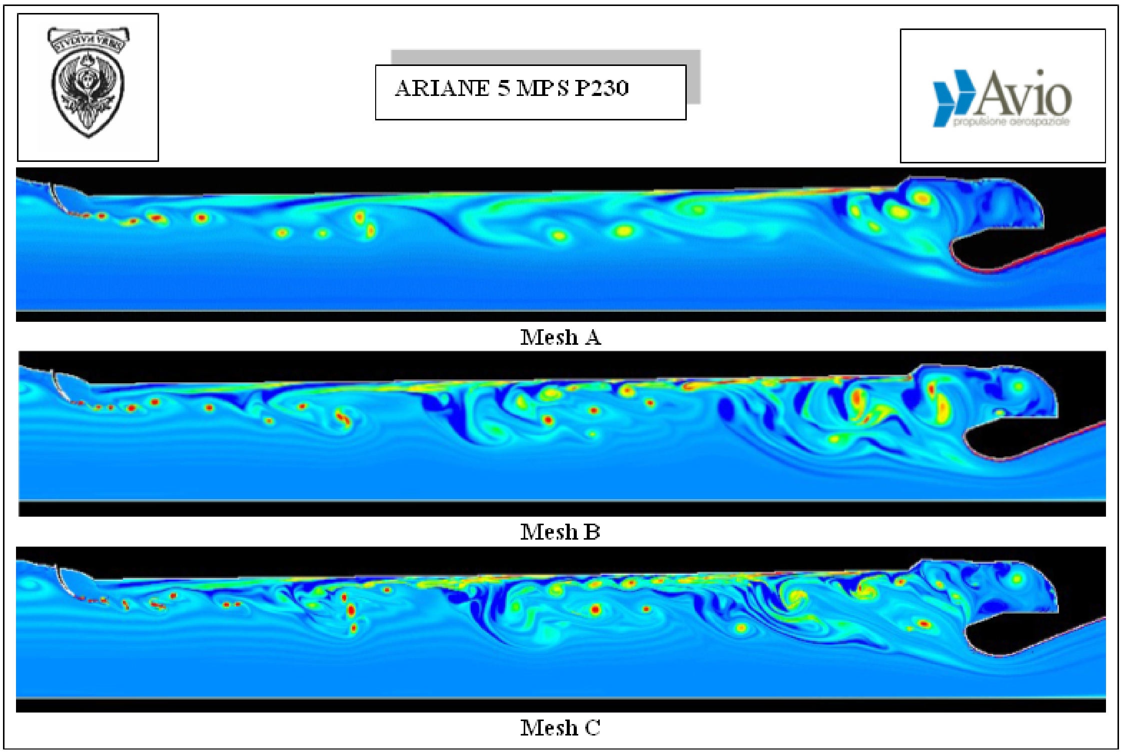

Fig. 5. Flow structure visualizations with the three meshes adopted (P230).

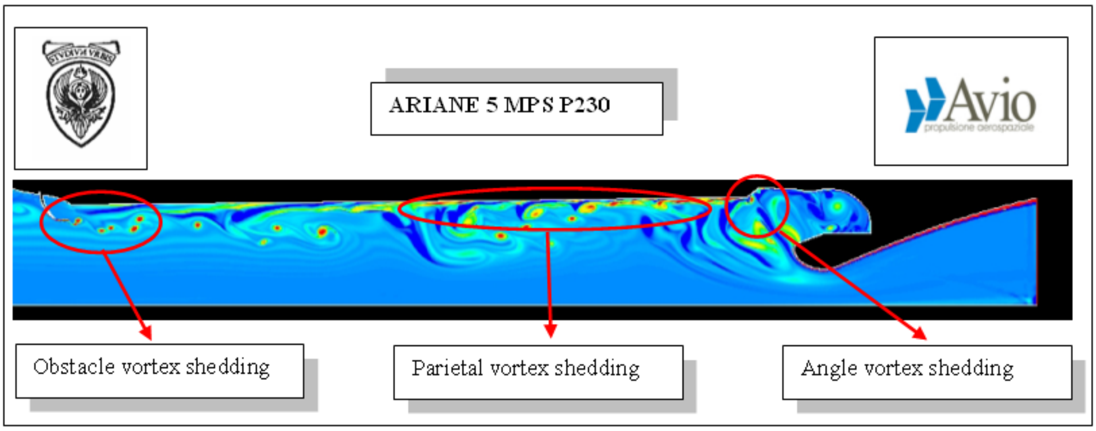

Fig. 6. The three mechanisms of vortex shedding (P230).

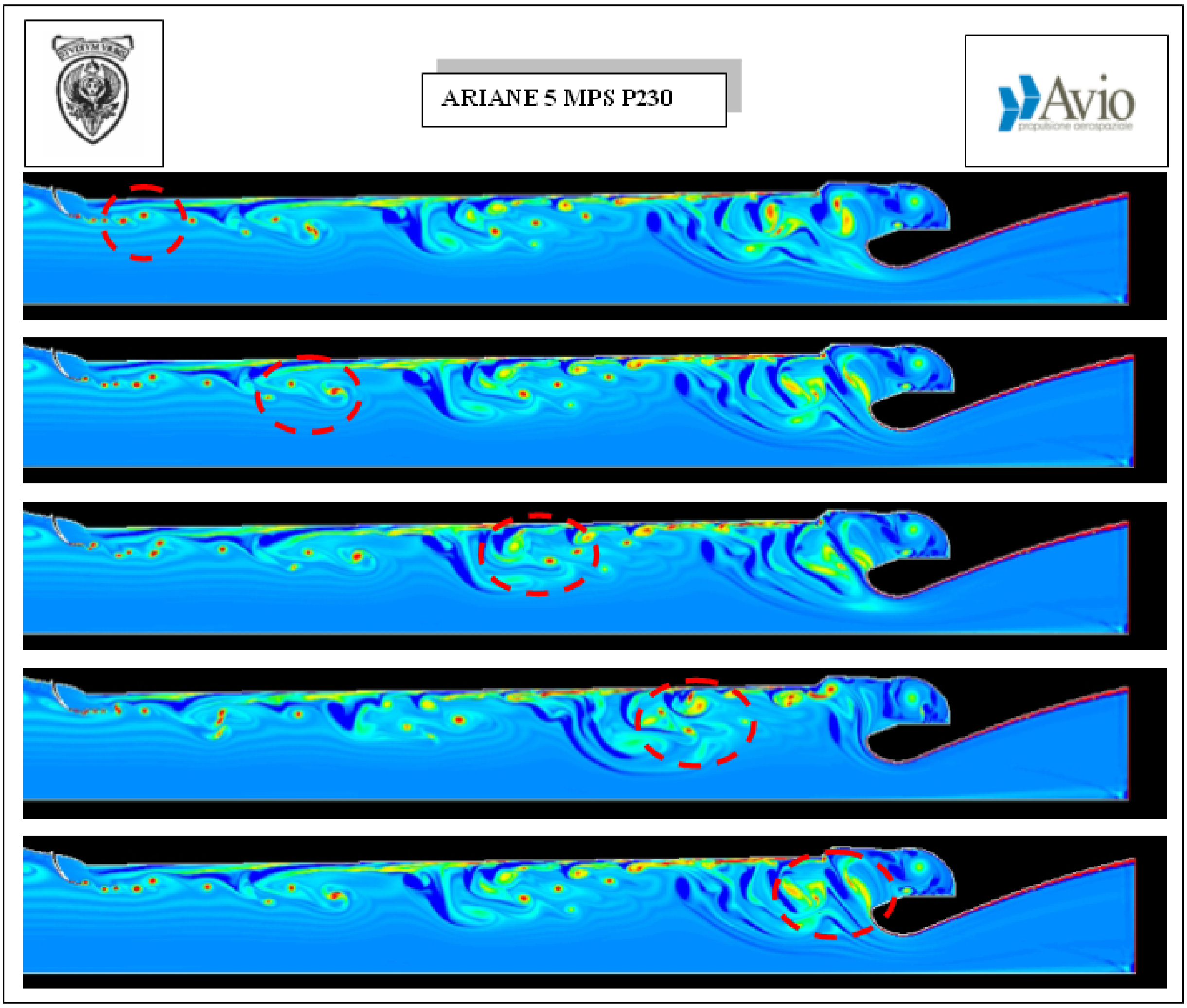

Figure 7. complete evolution of a single large flow structure (P230).

Conclusions

In the present paper numerical solution have been presented for small scale cold flow, small scale SRM (LP6) and full scale motor (P230).

Numerical results have been compared and validated against experimental data, showing in all cases an impressive numerical accuracy. CPU time requirements are also compatible with today computer capabilities and industrial applications.

In the case of numerical simulation performed on P230 SRM pressure oscillation amplitude shows a difference lower than 5% when compared with averaged flight data.

During the numerical simulations, all the three mechanisms of vorticity production (i.e. obstacle vortex shedding, parietal vortex shedding and angle vortex shedding) have been observed and properly reproduced.

It is worth noting that, presented results have been obtained only by means of CFD numerical simulation, showing the fundamental role that fluid-dynamics plays in pressure oscillation phenomenon. In the case of Ariane 5 P230, this is in contrast with the previous belief [10, 11] that a proper simulation on prediction of pressure oscillation levels necessary requires also modeling distributed combustion of aluminum.

On the basis of the presented results, further numerical simulations are in progress on different geometrical configurations and flow conditions in SRM. Moreover the proposed methodology is a suitable approach also for simulation three-dimensional SRM configurations such as flow conditions in ARTA 3 [12].

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