Non-stationary phenomena at the firing of a small thruster

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Introduction

In the framework of Ariane 5 program supported by CNES, the ONERA has carried out experimental studies of the blast wave which occurs at the ignition of solid-propellant rocket engines. Interesting shock wave or blast wave phenomena may be observed at a reduced scale. For instance, a thruster is a small rocket engine of very short combustion time, that allows to isolate the non-stationary phenomena occurring at its ignition : sound reflections off the ground, and shock waves. In the Fauga-Mauzac test center, a static thruster has been horizontally fired above a reflecting ground. The sound field has been measured along a linear microphone array aimed towards the nozzle, and along a large-radius nozzle-centered microphone arc. A unique shock wave occuring at the ignition was expected. Two successive shock waves were recorded in fact: the first one classically corresponds to the breaking of the nozzle shutter during the rise of the chamber pressure; the second one, more important, occurs during the short stationary phase of the chamber pressure. The latter phenomenon was surprising and has been studied more particularly. It is established, from three different methods (time lag of the reflected overpressure wave, spatial correlation functions, signal inlet chronology between the microphones), that the second shock wave comes from a point located at one meter downstream from the nozzle.

Experimental device

The thruster resembles to a classical rocket engine (Figure 1), but the powder grain is replaced by an aluminum tape covered with a thin layer of double-base propellant, the combustion time of which is very quick (20 to 30 ms). The engine has a strong chamber pressure (200 bar) during its steady state, and a small nozzle diameter (1 cm).

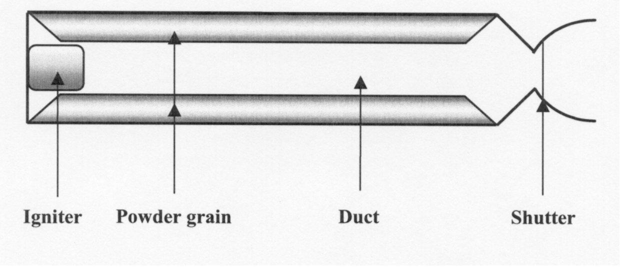

Figure 1: Classical solid-propellant rocket motor drawing.

The thruster is horizontally fixed above a concrete ground (Figure 2), the microphones are located in the nozzle plane, along a linear array from 2,5 m to 20 m outside the firing cell at 30° from the jet axis. Besides, a microphone arc of radius 20 m covers the angles 20° to 60°, with a step of 10°. The acquisition frequence of the time signal is 20 kHz.

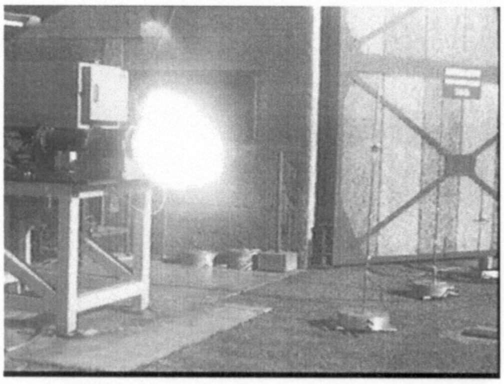

Figure 2: "Fireball" at the ignition of a rocket engine.

Classical phenomena

In the general case, two phenomena are observed at the ignition of a rocket engine (Figure 3): first, a shock wave train which occurs after the nozzle shutter breaking, pointed out by a temporary decrease of the chamber pressure; second, a blast wave which corresponds to a sudden pressure front followed by an underpressure time. This unsteady phase is very different from the steady phase of jet noise which follows after t = 0,27 s in Figure 3. We can remark that the blast wave generally occurs during the main rise of the chamber pressure, here from 10 bar to 40 bar.

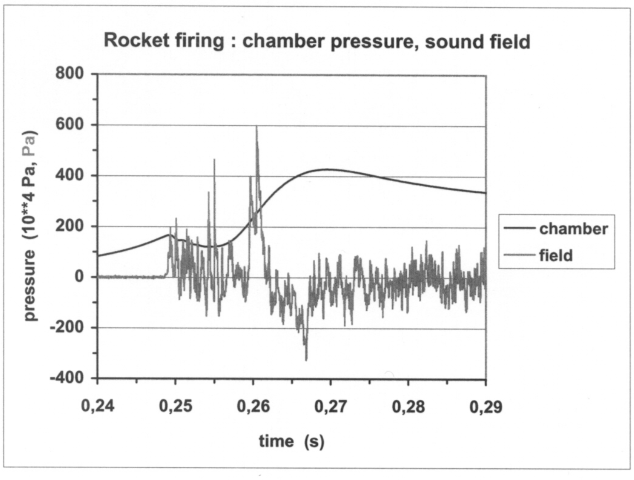

Figure 3: chamber pressure and far field signal recorded during the unsteady phase of a rocket firing.

In the literature, a correlation between the slope of the pressure rise and the overpressure intensity is often indicated. Otherwise, it is well known that the alternation of a strong and quick overpressure and a long underpressure time is typically the signing of a blast wave caused by an explosive chemical reaction. We know that the afterburning in contact with the air of some ejected gases (hydrogen, carbon monoxide) is a random phenomenon which can occur in the jet plume during both the steady and unsteady phases of the powder grain combustion. The gaseous “fireball” which appears after the shutter breaking has a great luminosity and a spherical or an ellipsoidal form (see Figure 2).

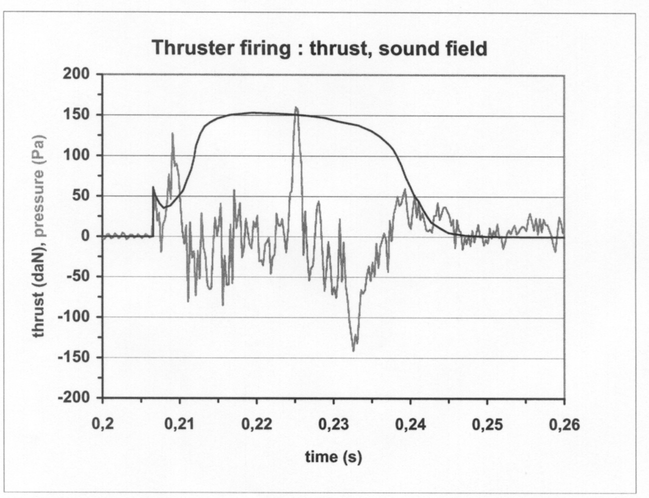

Figure 4: chamber pressure and far field signal recorded during the total duration of the thruster firing.

Thruster firing

Here we only give the experimental curve of the engine thrust (Figure 4), knowing that this thrust is narrowly correlated with the chamber pressure. A first shock front is recorded at the shutter breaking, followed by a second shock front (or a small blast wave) just before or at the start of the main thrust rise. However, a third shock front (blast wave) occurs during the steady phase of the thrust, and therefore of the chamber pressure, which is unexpected and surprising.

It was interesting to localize the apparent origin of the successive shock waves. A first method consists in the study of the signal autocorrelation for the microphones close to the nozzle, in order to determine the time lag between the direct sound field and the reflected sound field (note that the first purpose of the thruster firing was in fact to determine the transient response of this nonanechoic site). For a given signal window including, for instance, a shock wave, and for a given microphone located in near-field, it is easy to deduce from the time lag between the first peaks of the normalized autocorrelation function (Figure 5a) the theoretical position of the sound source, assuming that this “apparent” source is located on the jet axis. For the main blast wave (which occurs during the steady state of the jet), we found that the sound source is located at about D = 1 m from the nozzle.

A second method consists in determining the maximum value of the intercorrelation functions between a given near-field sensor and the sensors located along the arc of radius 20 m (Figure 5b): the maximum value is obtained for a given far-field sensor, the location of which gives the shock wave propagation direction. But this method gives uncertain results in the presence of a few number of microphones (12). We obtain the range D = 1 m ± 0.5 m from the nozzle.

The third method consists in the determination of the exact time of the arrival of a given shock front at the microphones. This exact time may be obtained by a direct reading of the time pressure signals, or by the calculation of the time lag between near microphones using the correlation function for the considered signal window. Thus, we establish the real chronology of the signal inlet and, knowing the sound velocity, we determine from a statistical method the best sound source location on the jet axis (which gives the same signal inlet chronology). We obtain :

- first shock front (shutter breaking): D ≈ 0 m,
- second shock front (thrust rise): D ≈ 0.4 m,
- third shock front (steady thrust): D ≈ 0.8 m.

Thus, the apparent source of the shock waves seems to follow the spatial expansion of the gaseous cloud.

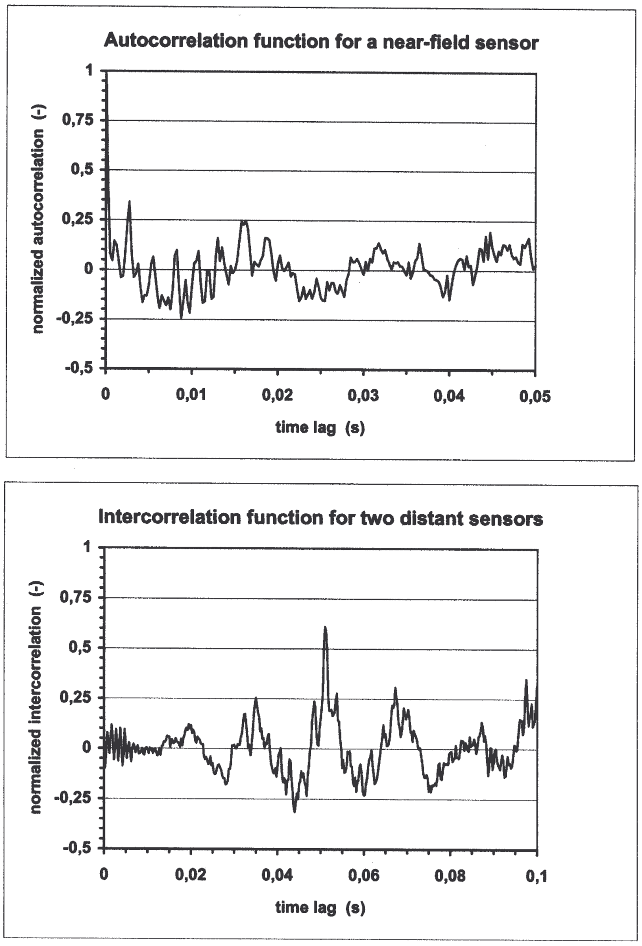

Figure 5: (a) autocorrelation function, (b) intercorrelation function between a near-field sensor and a far-field sensor.

Concluding remarks

The source of the shock waves seems to be not the nozzle exit (except the first one which results from the shutter breaking), but the gaseous cloud produced by the external expansion of the combustion products. The successive blast waves do not appear in this case very correlated with the chamber pressure history. More particularly, the second blast wave occurs during the stationary phase of the thrust and of the chamber pressure. We can make the hypothesis that this blast wave is related to a quick or explosive chemical reaction between the gaseous cloud and the oxygen of the ambient air. Infra-red movies of rocket engine ignitions seem to be necessary in the future for a best understanding of the phenomenon.