ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

BLAST WAVE AND AFTERBURNING AT IGNITION OF ROCKET ENGINES

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Abstract
In the framework “Sound Environment at Lift-off” of Ariane 5 launcher supported by the CNES, the ONERA has carried out several tests in order to study the transient phenomena at the ignition of small solid-propellant rocket engines. Here we present more particularly the tests aiming at determining a possible correlation between blast wave and afterburning of the ejected gases in contact with the air. For this purpose, acoustic, optic and infrared measurements have been made simultaneously during the static firings of two rocket engines.

INTRODUCTION

State of the Art

The blast wave, a brutal mechanical and acoustical phenomenon which generally occurs at the ignition of rocket engines - and more particularly of solid-propellant rocket engines - has non-continuous and unsteady characteristics which make difficult its experimental approach and modeling. In the present State of the Art, the origins of the blast wave caused by a rocket engine ignition do not seem totally known or clarified.

Let us note that the so-called “blast wave” designates two distinct phenomena in fact: the blast itself, i. e. the air movement caused by a brutal expansion of the combustion gases in ambient atmosphere, and the shock wave, a strong short overpressure front followed by a longer underpressure and by an infra-sound oscillation. These mechanisms have been carefully studied in the case of heavy guns [1].

More recently, the blast wave phenomenon has been amply studied in the case of chemical explosions [2] and also in the weapon domain [3], because of problems about acoustic discretion (acquisition by sound) and about optical discretion (muzzle flash of guns).

Other studies carried out with small-size military rockets have shown many similarities between their blast wave and guns blast wave. In fact, the chemical compositions of common solid propellants are very close to those of gunpowders and explosives. The models used for blast wave stem from explosion models, but the non-isotropic non-instantaneous character of the energy spreading into space must be taken into account in a more or less empirical manner [4].

For solid-propellant rocket engines of large size, such as the boosters of Space Shuttle or Ariane 5, the problem is even more difficult, since some phenomena (and more particularly chemical phenomena) cannot be transposed using a scale law. As for the launchers, the mechanical stress, caused by the direct blast wave (ignition overpressure) and the blast wave amplified by the jet ducts of the launch pad (duct overpressure), adds further to the vibro-acoustic constraint due to the jet noise [5].

In several studies, the blast wave intensity has been related to the slope of the chamber pressure rise, and therefore to purely mechanical causes. However, recent studies show that cooling of a jet by water addition can reduce the blast wave intensity in launch configuration [6]. This suggests that the reignition (or afterburning) of certain ejected gases (hydrogen, carbon monoxide) in contact with air may be an amplification factor for the blast, as it happens for heavy guns.

Experiments carried out at the ONERA

In the framework of Ariane 5 supported by the CNES, for some years the ONERA has carried out experimental studies based on the firing of static solid-propellant rocket engines at the Fauga-Mauzac Test Center. These small-scale rocket engines reproduce solid-propellant boosters of launchers (see Figure 1).

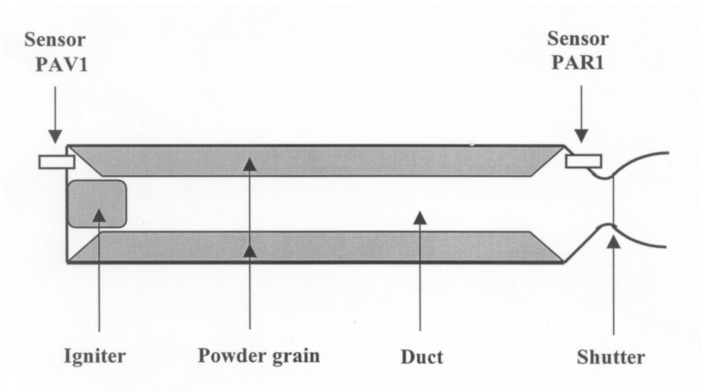

Figure 1 – Solid-fueled rocket engine drawing.

The aim of the acoustic measurements and analyses was to highlight the existence (or nonexistence) of a blast wave for small rocket engines on the one hand, to try to understand the phenomena occurring at the ignition on the other hand. In this paper, we examine in a first step the characteristics of the blast wave deduced from sound measurements. The phenomenon seems to be correlated with the history of the chamber pressure, but it also has a more or less random character.

For this reason, it was important to aim to determine the existence (or not) of afterburning at ignition of a rocket engine, and a possible correlation with the blast wave. That is why two rockets were tested in December 2005 with acoustic, optic and infrared measurements made simultaneously. These experiments are described in the second part of the paper.

BLAST WAVE AT THE IGITION OF A ROCKET ENGINE

Rocket engines and measurement device

The rocket engines are fastened on a solid support in a firing cell, around 1 m above the ground (see Figure 2). The jet opens out into free field, the microphones are fastened in the horizontal nozzle plan on masts allocated at various angles from the jet axis and at several distances from the nozzle (from 2,5 m to 20 m, according to the size of the rocket). The acquisition frequency is 20 kHz in general. Two pressure sensors are located in the combustion chamber, near the igniter and near the nozzle. The nozzle throat diameter is 2.5 cm (small size rocket) or 6 cm (medium size rocket), the rocket engines are fired with short or long nozzles and with various nozzle shutter breaking pressure – before its breaking, the aluminum shutter allows a rapid rise of the chamber pressure in order to make easier the ignition of powder grain.

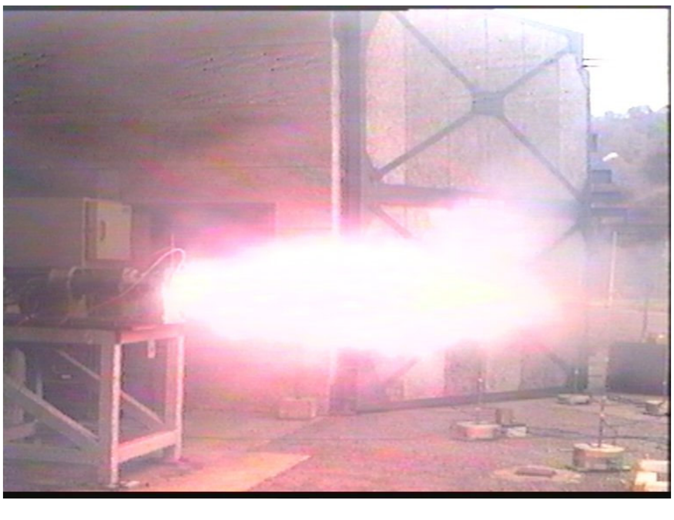

Figure 2 – Initial gaseous cloud at the ignition of a small-size rocket engine.

Several small-size and medium-size rocket engines were tested between 2001 and 2004 with an acoustic measurement device. These rocket engines were loaded with a non-aluminized solid propellant (ammonium perchlorate + hydrocarbon polymer) giving an exhaust fully-expanded Mach number close to 3 in stabilized rating. With the long nozzle (nozzle exit diameter: 7 cm), the small rocket engine has an over-expanded flow at the exhaust (static pressure: 0.6 bar). With the short nozzle (nozzle exit diameter: 4.5 cm), the small rocket engine has an under-expanded flow at the exhaust (static pressure: 1.7 bar). The ejected gases contain around 50 % of flammable gases (hydrogen and carbon monoxide).

Let us note that the igniter propellant mainly contains metals and potassium perchlorate. In transient conditions (Figure 2) the combustion products of the powder grain are mixed with those of the igniter: thus, the brightness of the gaseous cloud is mainly caused by these particles.

Experiments

In Figure 3 we can see the signal recorded by a chamber pressure sensor (in blue) during the firing of a small-size rocket engine with short nozzle. The rise of the pressure due to the igniter is suddenly interrupted by the shutter breaking, at around 16 bar. Next, the chamber pressure falls and rises again until 42 bar due to the powder grain ignition. The signal recorded by a microphone located in far field at 10 m downstream from the nozzle (in red) has been shifted to cancel the propagation time. We can remark:

– a first shock wave train following the shutter breaking and the initial gaseous cloud expansion;

– a strong overpressure front (until 700 Pa) followed by an underpressure time, the so called “blast wave”, which generally occurs during the main rise of the chamber pressure, the slope of which is around 3.3 bar/ms here;

– and finally the jet noise in stationary rating.

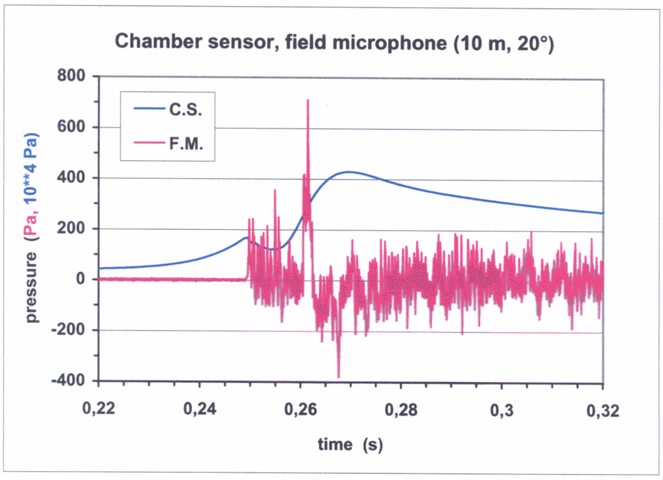

Figure 3 – Rocket firing: chamber pressure signal, far-field microphone signal.

Note that the blast wave does not occur with a slower chamber pressure rise, for example 1.6 bar/ms. This more or less random character of the phenomenon suggests that its causes may be not only mechanical. The same remarks have been made with the medium-size rocket engines (nozzle exit diameter: 18 cm, 30 % of flammable gases in combustion products): a first firing gave a strong blast wave, a second firing with quasi-identical chamber conditions gave a weak and delayed blast wave, after the main chamber pressure rise.

On the microphone arc of 10 m or 20 m in radius (according to the rocket size) centered at the nozzle exit between 20° and 60° from jet axis, we have noticed that the shock front following the shutter breaking reached all microphones simultaneously. In contrast, the blast wave arrival is recorded on the arc with significant time differences according to the microphone location, which suggests that the spatial origin of this wave is not the nozzle exit.

Then, two methods are possible to determine the preferential sound-propagation direction of the wave and its apparent origin on the jet axis: an analysis of the arrival times of the shock front at the microphones, or a computation of the correlation functions between the adjoining microphones during a time window including the transient phenomenon. Both methods give similar results. Let us note that the second method may be used with a very short window including the transient phenomenon (order of size 10 ms), but also with a large window to determine the sound power peak on the jet axis in stationary rating (see Table I). It appears that the apparent origin of the blast wave is located relatively far from the nozzle and at a short distance before this peak. Thus, it is highly likely that the wave train called "blast wave" is not produced in the nozzle region but by the developed gaseous cloud.

Table I - Apparent origin of the sound phenomena (distance from the nozzle, m).

Rocket size	Blast wave	Jet noise peak
Small	1.0 to 1.2 m	1.3 to 1.5 m
Medium	2.6 to 2.8 m	3.2 to 3.4 m

AFTERBURNING STUDY

General remarks, experimental device

Typically, the ignition of a small solid-propellant rocket engine is characterized by a shock wave following the nozzle shutter breaking. This shock wave has a maximum directivity in the axial downstream direction. A more important shock wave, here called "blast wave" by convenience, follows or not the first wave train. This phenomenon generally corresponds to the main chamber pressure rise and seems to be more or less correlated with the slope of this rise (if the slope is too slight, there is no external blast wave). The apparent origin of the first wave train is the nozzle region; the apparent origin of the blast wave train, when occurring, is the developed gaseous cloud.

These characteristics and others (random character, formation process) suggest a chemical origin for the blast wave train, maybe caused by the reignition of some combustion products in contact with the ambient air. This assumption is reinforced by the fact that recent "mechanical" CFD simulations for jets in free-field have not reproduced this phenomenon. For this reason, the ONERA and the CNES have decided to carry out tests with aluminized solid-propellant rockets, including acoustic measurements and optic and infra-red acquisition devices. It was expected to observe shock and reignition phenomena and to bring to the fore a possible time correlation between them. Two firings were made, the first with a long nozzle, the second with a short nozzle, in order to modify the shock cycle at the nozzle exit (the shocks are well known to go off afterburning).

The propellant used was a semi-aluminized composite propellant (5 % of aluminum in molar fractions) giving a chamber temperature close to 3,000 K and around 40 % of flammable gases at the exhaust.

One infrared camera (2,000 pictures/s) and two optical cameras (1,000 and 4,000 pictures/s) were located at around 10 m from the rocket, in directions more or less perpendicular to the jet axis. The acoustic measurement device was set up by ten microphones allocated on two nozzle-centered arcs of 5 m and 10 m in radius, and by one far-field microphone located at 15 m from the nozzle.

Results

The chamber pressure rise was very quick for the two firings: a slope of 4 bar/ms, a maximum pressure of 60 bar; there was no pressure fall between igniter and powder grain ignitions, and we have obtained both with long and short nozzles an immediate blast wave, as it is the case for guns. In the short nozzle firing case (Figure 4), we can see that the nozzle shutter breaking occurs at t_0 = 0.471 s and that the duration of the blast wave (overpressure-underpressure alternation) is about 11 ms.

In Figure 5, we can see in infrared luminescence the development of the initial gaseous cloud (short nozzle rocket firing). The maximum luminescence occurs at t_0 + 4 ms (i.e. at 0.475 s), which is well correlated with the sound phenomenon below.

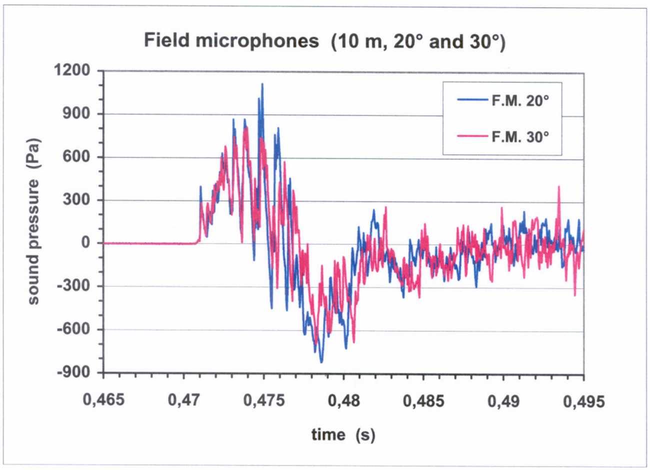

Figure 4 – Short nozzle rocket firing: blast wave and jet noise.

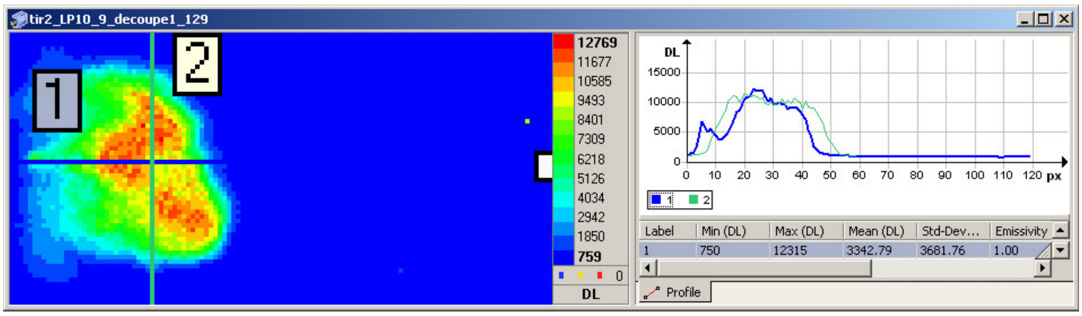

Figure 5 – Short nozzle rocket firing: infrared luminescence at t_0 + 4 ms.

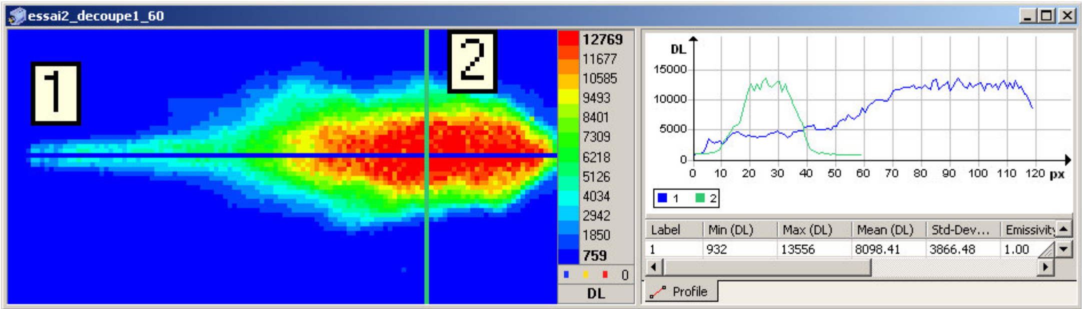

Figure 6 – Long nozzle rocket firing: infrared luminescence at t_0 + 5 ms.

Let us note that the cloud is quasi-spherical with the short nozzle (Figure 5), and not with the long nozzle (Figure 6). In both cases, a noteworthy result is the following: the "hot" part of the cloud is not close to the nozzle located on the left side of the pictures. This suggests that we are in presence of afterburning of the gases in contact with the air pushed away.

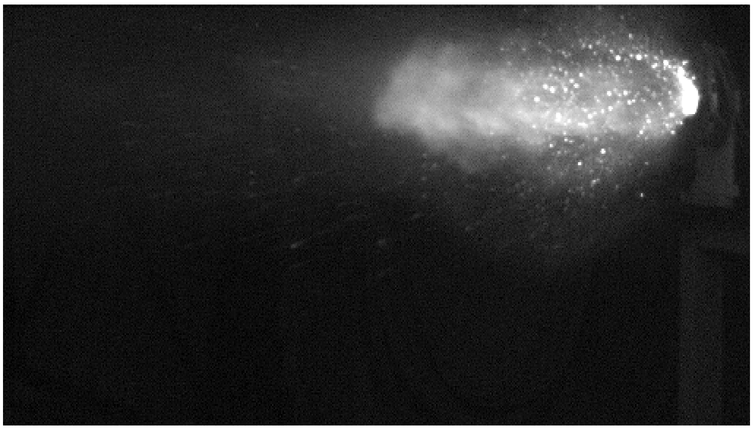

Figure 7 – Short nozzle rocket firing: alumina plug incident at t_0 + 1.54 s.

The optic views provide no new information, since the two cameras are more or less saturated by the brightness of the initial cloud. Yet an interesting phenomenon has been filmed at around t_0 + 1.54 s during the stationary rating of the jet, that is the shoot of an alumina plug which partly sealed the nozzle throat (Figure 7). This incident was accompanied by a strong overpressure front (over 1,200 Pa in far field). Unfortunately, the infrared camera was not running at this very moment.

CONCLUSIONS

The tests made with an infrared camera give very interesting results. Indeed, afterburning in the gaseous cloud occurs at the ignition time of the rocket engines, and this afterburning seems to be correlated with the simultaneous overpressure phenomenon. It is well known, in case of guns, that this reignition of ejected gases ("muzzle flash") strongly increases the sound level of the shot [1]. However this reignition may be chemically inhibited [3]. In the case of launchers, other attenuation mechanisms must be searched (water injection), since the reignition cannot be chemically neutralized when aluminized propellants are used. In all cases, the mechanism of the blast wave may be clarified by other experiments, for instance by using a ultra-violet camera in order to detect the ions which characterize the combustion.

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