JOURNAL OF PROPULSION AND POWER
Vol. 15, No. 6, November–December 1999

Solid-Propellant Combustion Response Function from Direct Measurement Methods: ONERA Experience

Franck Cauty*
ONERA, BP 72-F92322 Châtillon CEDEX, France

Usually, the pressure-coupled response function of a solid propellant is determined using the traditional indirect methods such as T-burner or modulated exhaust jet technique. A few direct methods, based on wave propagation through the solid-propellant grain, exist: microwave and ultrasound techniques. There is also the magnetohydrodynamic technique derived from magnetic velocimetry through the gas phase. The theoretical approaches of each method are explained and are coupled with an acoustic analysis of the pressure oscillations. The response function is determined using these direct and nonintrusive methods for the Ariane V solid propellant (HTPB–AP–Al) and a nonmetalized propellant. Results obtained for composite propellants, such as that of the Ariane V, show the accuracy of each method and underline the advantages or disadvantages of each method as far as ONERA's experience can carry it out. Direct methods are nonintrusive but are limited because of their principle itself. There is a frequency limit above which the measurement cannot be performed. Finally, the objectives of future ONERA work are proposed.

Nomenclature

A = kinetic parameter in the response function, $(1 - T_i/T_s)(E_s/R_0T_s)$
A_b = acoustic admittance of the burning surface
a = thermal diffusivity, m/s^2
a_0 = speed of sound, m/s
B = parameter in the response function, $[\sigma(T_s - T_i)]^{-1}$ or magnetic flux density, Wb/m^2
C = mechanical wave velocity, m/s
C_i = corrective coefficients
d = distance between the electrodes, mm
E = thickness, mm; electric field strength, V/m
e = output voltage, V
f = frequency, Hz
k = mechanical wave sensitivity coefficients for the propellant, K^{-1} or MPa^{-1}
l = mechanical wave sensitivity coefficients for the coupling material, K^{-1} or MPa^{-1}
M_0 = Mach number
$\dot{m}$ = mass flux, kg/s
$n_{(P)}$ = burning-rate pressure exponent, $(\partial \ln V_b/\partial \ln P)_{T_0}$
P = pressure, MPa
R_{MP} = response function, $(\dot{m}'/\bar{\dot{m}})/(P'/\bar{P})$
S = ratio of propagation-time amplitude to pressure amplitude, both reduced with respect to their mean value, $(\tau'/\bar{\tau})/(P'/\bar{P})$
s = root of characteristic equation, $s(s-1) = i\Omega$
T = temperature, K
t_s = residence time, ms
u = gas velocity, m/s
V_b = burn rate, mm/s
x = distance between the electrodes and the burning surface, mm
Z = complex coefficient of reflection, $X + iY$
α = nondimensional coefficient
γ = ratio of specific heats
$\Delta\phi$ = phase shift, deg
ρ = gas density, kg/m^3
σ = temperature sensitivity coefficient of burning rate, $(T_s^0 - T_0)(\partial \ln V_b/\partial \ln P)$
τ = mechanical wave propagation time, μs
Ω = nondimensional frequency, $a\omega/V_b^2$
ω = angular frequency, rad/s

Subscripts

CF = cold flow
c = coupling material
ini = initial conditions
P = pressure
p = propellant
ref or 0 = reference conditions
s = surface
T = temperature

Superscripts

i = imaginary part
r = real part
$\bar{()}$ = mean quantity
$()'$ = fluctuating quantity
$*$ = apparent or noncorrected quantity

Introduction

BESIDES the traditional indirect methods for determining solid-propellant response, such as the T-burner or the modulated exhaust jet technique, a few direct methods exist. Based on wave propagation through the solid-propellant grain, there are the microwave technique (MWT) and the ultrasound technique (ULT). There is also the magnetohydrodynamic (MHD) technique derived from magnetic velocimetry through the gas phase.

ONERA's experience in such direct methods is presented. ONERA has been involved in the development of microwave and ultrasonic measurement techniques for low-frequency pressure-coupled response determination in the framework of the Ariane V booster assessment. Furthermore, ONERA has been investigating the MHD technique following the work done by Wilson and Micci[1] at Penn State University. The microwave technique has been evaluated widely by different research teams: Strand et al.[2] at Jet Propulsion Laboratory, Russell[3] at Naval Surface Warfare Center, and Wood et al.[4] at the Virginia Polytechnic Institute and State University. The ultrasound method is more a French technique devoted for burning-rate determination.

Received 17 February 1998; revision received 20 July 1998; accepted for publication 30 July 1998.

*Research Scientist, Fundamental and Applied Energetics Department.

These three direct methods require a modulated exhaust-jet setup to generate pressure oscillations at a selected frequency. These oscillations are produced by means of a toothed wheel rotating over the exit of the nozzle. Sensors and devices are specific depending on the method: microwave horn with microwave analyzer (MWT), ultrasonic transducer and electronic device for ultrasonic measurement (ULT), and electric probes with a permanent magnet (MHD). These technical tools are described. Their theoretical approaches are coupled with an acoustic analysis of the pressure oscillations: cavity waves for MWT and ULT or part of a standing wave for MHD. They are explained shortly.

Description of the Methods

The ONERA modulated-exhaust-jet technique (MEJT) was developed in the early 1970s. This technique is based on the production of (forced) oscillations in a (reduced-volume) combustion chamber by means of a modulating wheel that partially and periodically interrupts the nozzle throat. This setup is shown in Fig. 1 for ULT. The modulation-wheel profile can be a sine oscillation (low-frequency range) or square tooth (higher-frequency range). An optic-fiber apparatus provides a reference signal related to the throat modulation. This system is put on the rotating wheel on the MHD setup or on a second smaller wheel for ULT and MWT.

The MWT experimental setup uses the sample-generator modulated-exhaust-jet technique drawn in Fig. 2. The operating pressure is obtained through a main unmetallized propellant grain. The MHD setup is small because it has to be put between the poles of a magnet (Fig. 3).

Grain geometry characteristics are as follows: Diameters are 85 mm for ULT, 36 mm for MHD, and 10 mm for MWT; the strand thickness is always around 20–30 mm. The propellant sample size is small. This reduces test cost, but the modulated throat size is very small and the pressure level is difficult to adjust. The mean pressure often varies during the combustion because of deposits between the throat and the wheel, modifying the initial gap. Of course, this effect is stronger with aluminized solid propellants. During the test, this deposit can be ejected or not. Erosion of the wheel profile by hot gases also modifies the pressure level, especially the unsteady component.

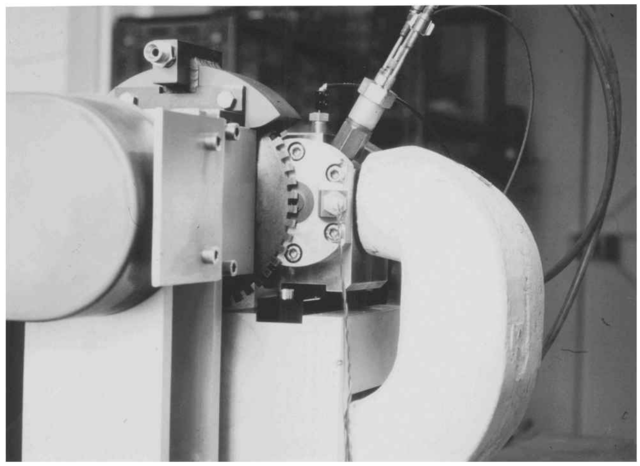

Fig. 3 MHD setup.

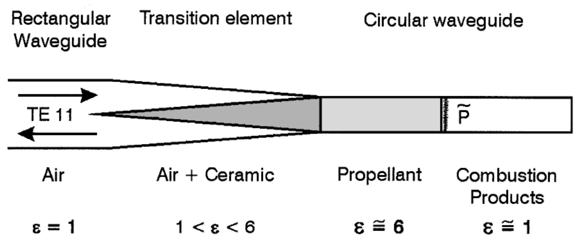

Fig. 4 Principle of the MWT.

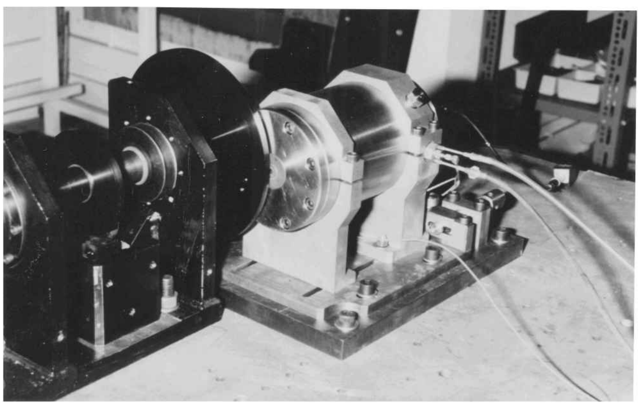

Fig. 1 Setup for modulated exhaust-jet technique.

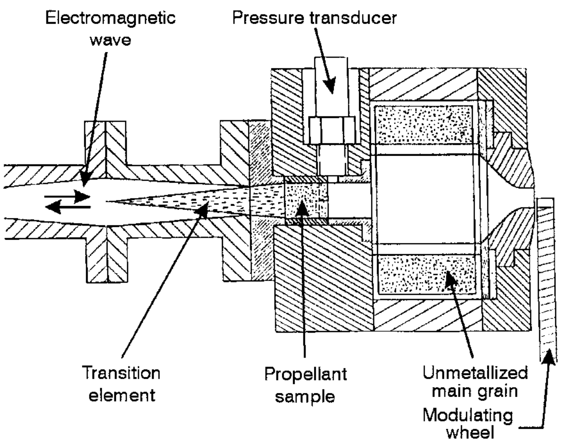

Fig. 2 Microwave experimental setup.

The measurement processing is basically the same for these three methods: The pressure and the specific measurement signal are digitized for the mean value as well as for the unsteady component, which is filtered in the suitable frequency range. The unsteady oscillations are analyzed using the same data processing method to give the zero-peak amplitude and the phase window by window. A phase shift is computed with respect to the reference pressure signal.

These are general considerations, but each method requires specific test conditions and sensors. Each technique is discussed in the following sections.

MWT

The fundamental principle of the method[5,6] is derived from the propagation of electromagnetic waves ($f = 10$ GHz) in absorbing materials. The propellant sample is fitted in a cylindrical waveguide. A microwave source creates the electromagnetic wave, which travels through rectangular microwave guides, then through a conical transition element, and finally through the propellant sample (Fig. 4).

A quasi-complete reflection occurs on the burning surface. The instantaneous measurement of the phase shift between incident and reflective waves is directly proportional to the thickness of the propellant sample. The time derivative of the phase shift gives the unsteady burning rate. The microwave signal is obtained from a microwave analyzer designed and developed at ONERA in 1990. This apparatus measures the complex coefficient of reflection from the transition element (Z). The assumed linearized relationship between the experimental signal and the phase shift with ω the pulsation frequency is

$$Z = X + iY$$

$$R_{\mathrm{MP}} = \left(\frac{i\omega}{P'/\bar{P}}\right)\left[\frac{X' + iY'}{(\mathrm{d}X/\mathrm{d}t) + (i\,\mathrm{d}Y/\mathrm{d}t)}\right]$$

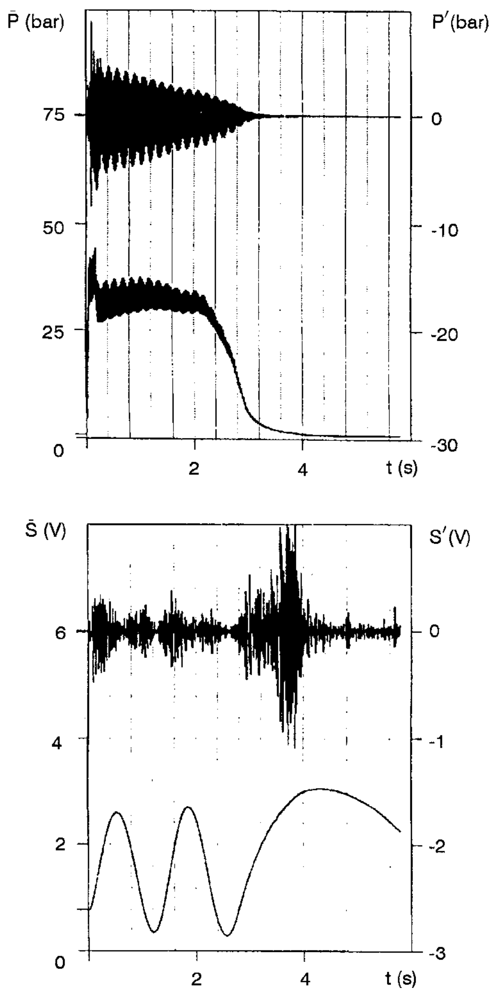

Fig. 5 Microwave interferometer device: basic results.

The response function is computed by deducing ω, P', and $\bar{P}$ from the pressure measurements and X', Y', $\mathrm{d}X/\mathrm{d}t$, and $\mathrm{d}Y/\mathrm{d}t$ from the microwave measurements (Fig. 5). Each parameter of the R_{MP} relationship is determined; thus the response function is obtained for many analysis windows through the test.

The response-function values obtained from these signals lead to a few remarks. First, the computed response function is not constant during a test at constant pressure. Second, the response functions measured above 200 Hz seem to be high compared to data obtained by indirect methods. Third, the existence of a linear relationship between the phase shift and the propellant thickness is only partially true: The phase shift is only the argument of the complex coefficient of reflection from the transition element and the question arises as to the meaning of the modulus. A model has been proposed that takes into account the piling of various waveguide elements. For metallized propellants, the amplitude of X' (or Y') is not zero when $\mathrm{d}X/\mathrm{d}t$ (or $\mathrm{d}Y/\mathrm{d}t$) is equal to zero. In short, we can say that this phenomenon is turned into a second response term corresponding to a response to pressure oscillations of the coefficient of reflection from the burning surface[5] or to an apparent response obtained from a cold-flow test.[6] The authors note that the basic question of all direct (and indirect) measurement methods is: What is really measured? This point is examined later.

ULT

For MWT, the phase shift is related to the thickness. For ULT,[7,8] the return propagation time is proportional to the thickness by means of an acoustic velocity C, which, unfortunately, varies with stress–strain distribution and thermal profile. A theoretical approach to the ultrasonic measurement analysis under unsteady conditions has been proposed in Ref. 7. The final relationship shows that the apparent response has to be corrected:

$$(R_{\mathrm{MP}})^r = \frac{C_3\left[\left(R^*_{\mathrm{MP}}\right)^r + C_1\right] + C_4\left[\left(R^*_{\mathrm{MP}}\right)^i - \Omega C_2\right]}{C_3^2 + C_4^2}$$

$$(R_{\mathrm{MP}})^i = \frac{C_3\left[\left(R^*_{\mathrm{MP}}\right)^i - \Omega C_2\right] + C_4\left[\left(R^*_{\mathrm{MP}}\right)^r + C_1\right]}{C_3^2 + C_4^2}$$

Coefficients C_1–C_4 are defined by

$$C_1 = \frac{k_P \bar{P}}{[1 - k_P(\bar{P} - P_{\mathrm{ref}})]}$$

$$C_2 = \frac{1}{[1 - k_P(\bar{P} - P_{\mathrm{ref}})]}\left\{k_P \bar{P}\left[\frac{E_p V_b}{a} + k_T(\bar{T}_s - T_{\mathrm{ref}})\right] + l_P \bar{P}\frac{C_{p\mathrm{ref}}}{C_{c\mathrm{ref}}}\frac{E_c V_b}{a}\right\}$$

$$C_3 = 1 + k_T(\bar{T}_s - T_{\mathrm{ref}})\left[1 - \frac{s^r}{(s^r)^2 + (s^i)^2} + \frac{1 - s^r}{A}\right]$$

$$C_4 = k_T(\bar{T}_s - T_{\mathrm{ref}})\left[\frac{s^i}{(s^r)^2 + (s^i)^2} - \frac{s^i}{A}\right]$$

These corrective terms represent physical influence parameters. The coefficient C_1 is a function of pressure and propellant ultrasonic velocity sensitivity to pressure k_P. Its value is small—a few hundredths. For C_2, instantaneous propellant thickness E_p, coupling material characteristics ($C_{c,\mathrm{ref}}$, l_P), geometry (E_c), and the steady combustion thermal profile must be added. C_2 is much larger because of the propellant thickness which, of course, decreases during the combustion. At the end of burning, this coefficient represents the coupling-material contribution. C_3 and C_4 coefficients depend on the thermal profile via the temperature sensitivity of the wave velocity k_T and propellant kinetics. They are based on composite propellant combustion model ($s = s^r + i s^i$) (Ref. 9). The influence of the kinetic parameter A, from Arrhenius law, on C_3 and C_4 is small at low frequency, below 100 Hz (Ref. 8).

The ultrasonic measurement allows one to determine the apparent response function R^*_{MP}. This function can be calculated from

$$\left(R^*_{\mathrm{MP}}\right)^r = (\omega \bar{E}_p/\bar{V}_b)|S| \sin \Delta\phi$$

$$\left(R^*_{\mathrm{MP}}\right)^i = -(\omega \bar{E}_p/\bar{V}_b)|S| \cos \Delta\phi$$

with ω the pulsation frequency, $\Delta\phi$ the phase shift between ultrasonic and pressure signals, E_p the propellant thickness, V_b the burning rate, and S the ratio of the propagation-time amplitude and of the pressure amplitude, both reduced with respect to their mean values.

The data reduction software is split in three parts. The first part is common for all unsteady measurement processing: one determines the zero-peak amplitude and the phase shift between the unsteady signal and its specific reference signal, step by step, in a small time interval. For the ultrasonic measurement, the unsteady signal is the unsteady propagation-time variation and the reference is the unsteady pressure. Then, in a second part, mean pressure, mean propagation time, propellant thickness, and burning rate are computed and added to the unsteady output file at each interval of time. The third part computes the pressure-coupled response function using the appropriate theory for MEJT.

As seen through the relationships, various parameters influence the results: coefficients of mechanical wave velocity, propellant surface temperature and diffusivity, and the corrective coefficients C_1–C_4. The pressure transducer calibration and the transfer function

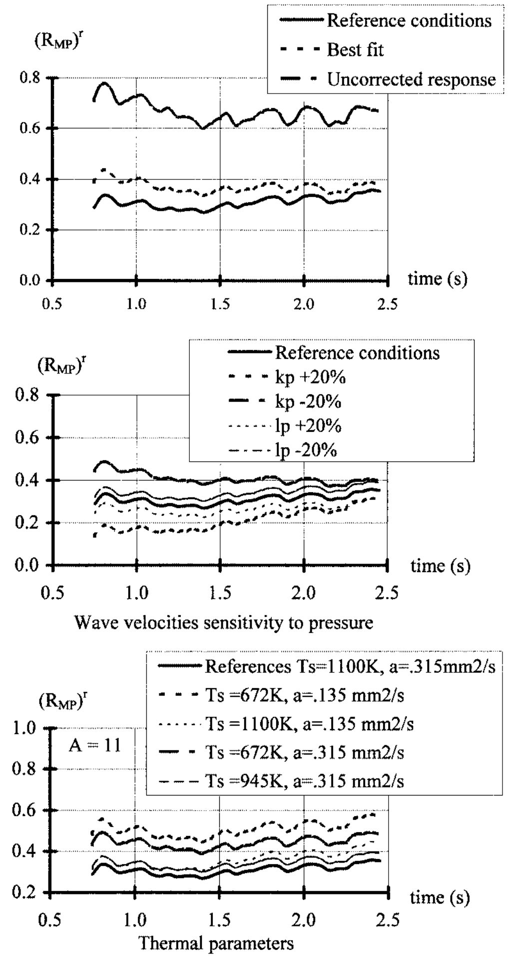

Fig. 6 ULT parametric study.

of unsteady pressure and propagation time modify S and $\Delta\phi$. They also must be quantified. This parametric study is represented on Fig. 6. The basic assumption is that the response function (its real part) is constant during the test. The value of S is known within a maximum scattering of 4%. The thermal parameters' influence is also in the same range. The effect of k_p and l_p on response level is greater. The best fit obtained gives a quasi-constant value of the real part of the response function $(R_{\mathrm{MP}})^r$. Thus, the accuracy of the method depends on having a good knowledge of the corrective terms, which are valid only if the theoretical analysis is valid.

MHD

This third method is the only one based on a gas-phase measurement. Here, the pressure and velocity oscillations in the combustion gases above the surface of the burning solid propellant are measured. The nondimensionalized ratio of the velocity to the pressure oscillations gives the complex acoustic admittance of the burning surface from which both the real and imaginary parts of the pressure-coupled response can be calculated. The method was developed by Micci et al.[1] and has been combined with an acoustic analysis of the standing wave above the surface of the solid-propellant grain.[10] In the magnetic flowmeter burner, the velocity of the gases is measured by applying a strong magnetic field and measuring the strength of the electric field generated by the ionized combustion-product gas moving through the magnetic field. The electric field is equal to the cross product of the gas velocity and the magnetic field: $E = u \otimes B$.

The electric field is measured by placing two electrodes in the periphery of the flow at right angles to both the magnetic field and the flow direction. The measured voltage is given by $V = \alpha u B d$, where α is a nondimensional coefficient 0–1.

The improved magnetic flowmeter burner combines the MEJT (forced pressure oscillations) and ultrasound measurement (distance between electrodes and burning surface). The size of this burner is small because of the distance between the two magnetic poles. The electrodes are the most important technical point of the MHD setup.

The acoustic analysis is based on the assumption that the mean flow properties, the frequency of oscillation, the burning surface, the nondimensional coefficient α, and the propellant acoustic admittance are constant during a test and that the mean flow and the oscillations are one-dimensional. A further assumption is that there is no feedback effect from the force generated by the magnetic field on the mean or unsteady flowfields.

The reduced ratio of velocity to pressure oscillation can be written as

$$\frac{u'}{p'} = \frac{1}{\rho_0 \cdot a_0} \cdot \left[-\exp\frac{i \cdot \omega \cdot x}{a_0 \cdot (1 - M_0)} + \frac{1 + A_b}{1 - A_b} \cdot \exp\frac{i \cdot \omega \cdot x}{a_0 \cdot (1 + M_0)} \right] \Bigg/ \left[\exp\frac{i \cdot \omega \cdot x}{a_0 \cdot (1 - M_0)} + \frac{1 + A_b}{1 - A_b} \cdot \exp\frac{i \cdot \omega \cdot x}{a_0 \cdot (1 + M_0)} \right]$$

$$\frac{e'}{p'} = \alpha \cdot \frac{u'}{p'}$$

These equations give, at any time during the firing, values for the acoustic admittance of the burning surface A_b and α the MHD gain. Because the acoustic admittance at the surface ($x = 0$) is related to the pressure-coupled response, the response function R_{MP} is determined:

$$R_{\mathrm{MP}} = (A_b / \gamma M_0) + 1$$

Results

In parallel to presenting these results, examples of the intermediate results, such as amplitude and phase shift, also are given and compared to what is expected from the inverse analysis. A discussion is opened on the quality and accuracy of these direct methods, pointing out their strengths and weaknesses.

Ariane V Composite Propellant

This solid propellant is well known[6,7,11]: an HTPB–AP propellant with an aluminum content of 18%. The measurements performed on this propellant via ULT consist of tests modulated at very low frequency (80 Hz max) and fired between 4.4 and 6.7 MPa (Ref. 7). As drawn in Fig. 7, the ratio of reduced amplitudes S has an initial value of 1.5–2%. This ratio increases during the test because of the decreasing propellant thickness. The phase shift between unsteady propagation time and pressure varies from 175–173 to 172–167 deg during combustion. This phase shift takes into account the time delay between mechanical wave reflection on the burning surface and its arrival on the transducer.

The reduced amplitude and phase shift of the test lead to an apparent response-function R^*_{MP} value that can be separated into a quasi-constant real part and an imaginary part, which decreases as the propellant grain burns (Fig. 8). The real part diminishes when the influence of the parameters is taken into account via C_1–C_4 coefficients. The slope of the imaginary value is proportional to pressure level and ultrasonic velocity sensitivity to pressure k_p. The C_2 coefficient corrects the imaginary part, which ranges between -0.2 and 0.1.

An inverse computation has been performed. Its aim was to determine what unsteady measurement behavior should correspond to a fixed pressure-coupled response value. There is a fairly good agreement as shown by the intermediate result S and $\Delta\phi$ in Fig. 7 because they have the same mean feature as the measurement.

The theoretical approach seems to be accurate enough and no out-of-range result is seen. The accuracy of this method decreases as the frequency increases inducing a bad signal-to-noise ratio. This change can be explained by looking at the sample thickness. The zero-peak unsteady propagation time (once translated into thickness) varies from 80 μm at 20 Hz to 15 μm at 80 Hz (Fig. 9).

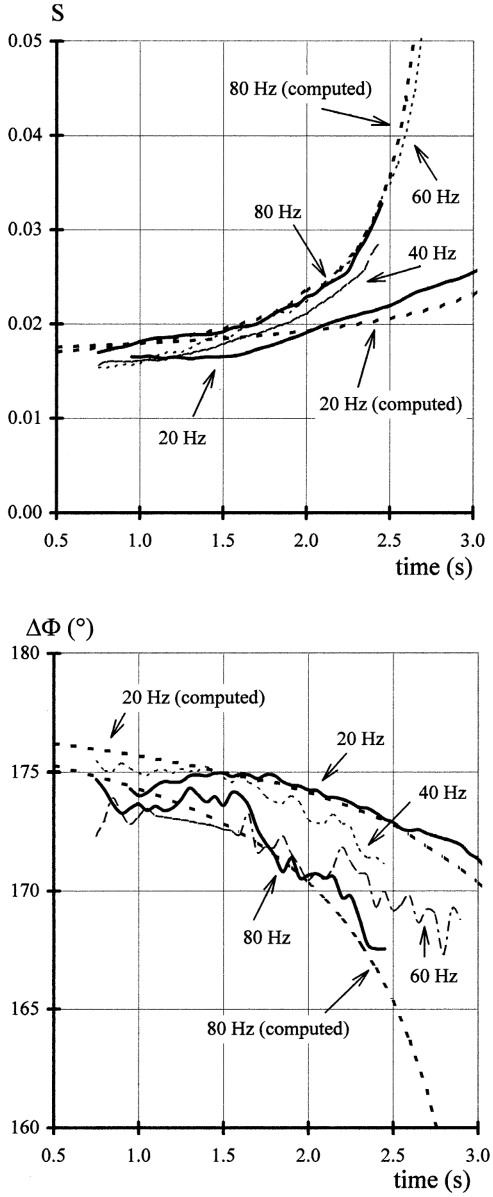

Fig. 7 Reduced amplitude and phase shift of ULT.

Furthermore, this is at the beginning of the test when the modulation level is at its highest.

This behavior results in the main limitation of this method, which is an operating frequency below 100 Hz, which is too low for many applications. The accuracy of the method also is not yet verified completely. Response values close to and slightly above the pressure exponent of the burning-rate law have been found. A comparison with microwave results is helpful.

In 1991, tests were performed on Ariane *V* solid propellant using MWT.[6] The mechanical response of the grain, which is called cold-flow response R_{CF}, was measured systematically before the firing. The smaller the effect, the more reliable is the result. Response values during a combustion test show a scattering around an average value but also an evolution with time. This evolution is probably due to some fundamental problems associated with microwave propagation or the influence of the mechanical behavior of the sample (high R_{CF} increases this effect).

MWT values of the response function have the same tendency as ULT response values with frequency (Fig. 10). It can be concluded that the real part increases slightly from the pressure exponent value to 1 at 100 Hz. Standard deviation is smaller for ULT values than for the MWT values. Mean values of the real part of the pressure-coupled response function are plotted on Fig. 10 with results obtained at higher frequencies by indirect methods.

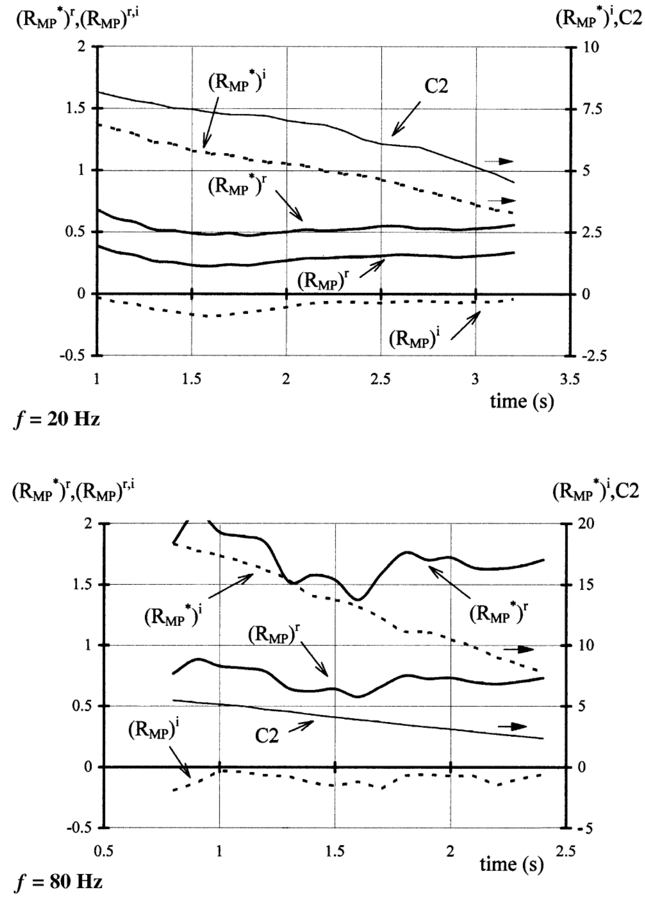

Fig. 8 Real and imaginary parts of the response function of ULT.

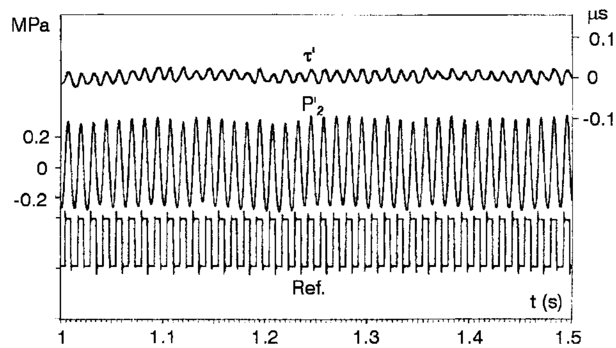

Fig. 9 Example of unsteady components in ULT.

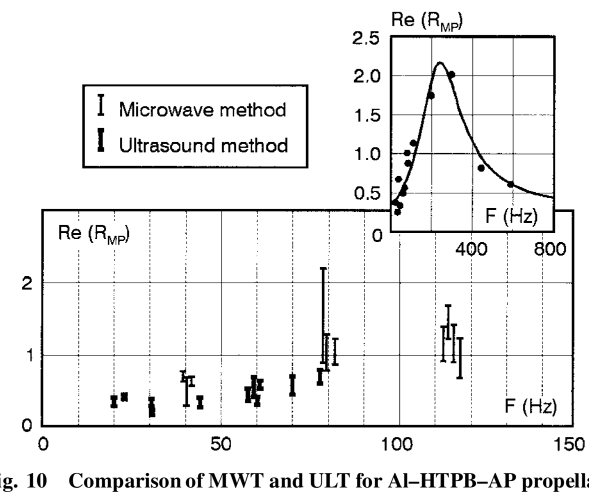

Fig. 10 Comparison of MWT and ULT for Al–HTPB–AP propellant.

A least-squares regression curve is drawn through these values, following the theoretical response law for composite propellant:

$$R_{\mathrm{MP}} = \frac{n_{(\bar{P})}AB}{s + (A/s) - (1 + A) + AB}$$

The adjustment gives acceptable values: $A = 8.90$, $B = 0.687$, and $a/V_b^2 = 4.56 \times 10^{-3}$ s for $n(P) = 0.34$.

When the MHD technique is used, the frequency range changes. Two tests were conducted with the Ariane V solid propellant at a modulation frequency of 600 Hz. The MHD velocity signals were difficult to interpret because their levels were changing drastically at any given time. This results in an unrealistic value for the pressure-coupled response. However, there is a strong level on the unsteady component of the MHD signal for such a metalized propellant, as opposite to nonmetalized propellants.

Nonmetalized Composite Solid Propellant

A nonmetalized solid propellant[8,10,12] was initially selected for testing the ability of ULT to give data related to the pressure-coupled response function.[8] The theoretical hypotheses were verified on these tests. The main characteristics of the two tests carried out in 1988 are presented in Table 1.

The nondimensional pressure level is over 20% at the beginning of the burning. The residence time lasts 10 ms. At these low frequencies, the real part of the response function is close to the pressure exponent of 0.3. Notice the imaginary part almost equals zero.

It is on this propellant that the MHD method was first applied. Once the setup was improved, the MHD signals seemed to follow the expected behavior (Fig. 11). The mean MHD velocity signal shows a step after the electrodes reached the burning surface and is kept constant as long as the grain burns, like a velocity measurement. The unsteady component appears on this signal.

Filtered and amplified, this signal evolution is compared to those determined from the MHD analysis using an inverse computation. From a given value of the response function, the unsteady signal that should be measured for the initial response level is computed (Figs. 12a and 12b). On the whole, the measured and computed gains and the phase shifts behave similarly. The maximum sensitivity of the MHD method is obtained when the electrodes are close to the propellant surface. The problem is that, at this time, the amplitude is tiny even if the phase shift is large. Thus it is difficult to determine an accurate result under such conditions.

Unfortunately, no other test gave such a result: The time evolution does not follow the rule, except for only a few data windows per test. This led to performing new tests using the same propellant and changing parameters that have a strong effect on the MHD signal. These parameters are the distance between the two tungsten electrodes, how they are fitted, their diameter, and their length into contact with the gases. However, no effect was evident when KCl was added to the propellant to increase the plasma conductivity. Because the unsteady MHD signal amplitude seemed to be higher for hotter gas temperature (due to aluminum), a thermoelectronic emission effect could be suspected. Tests without the magnet, and therefore without any MHD effect, were fired and gave the same results as those run before with the magnet. Is the MHD effect hidden by something else? To confirm this, a test was conducted where the electrodes were heated by a welder's torch with the modulation of the throat, but without the magnet and without the solid-propellant sample. The result is drawn in Fig. 13 with the classical MHD signals for metalized and nonmetalized solid propellants. Finding a difference between these signals is quite difficult. It could only be seen from the detailed qualitative MHD signal spectra. Notice that the MHD level is related to the characteristics of the measurement circuit. For example, on the inert test MHD signal drawn here, the resistance was increased from 10 kΩ to 1 MΩ, and the MHD level was drastically amplified.

Table 1 Characteristics of tests of ULT

f, Hz	P, MPa	P'/P, %	t_s, ms	$(R_{\mathrm{MP}})^r$	$(R_{\mathrm{MP}})^i$
40.20	2.98	29.8	10.4	0.453	0.024
60.08	3.01	19.5	10.9	0.309	0.094

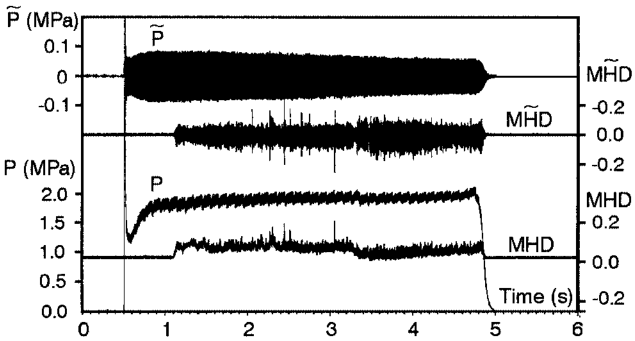

Fig. 11 MHD signals from the ONERA device.

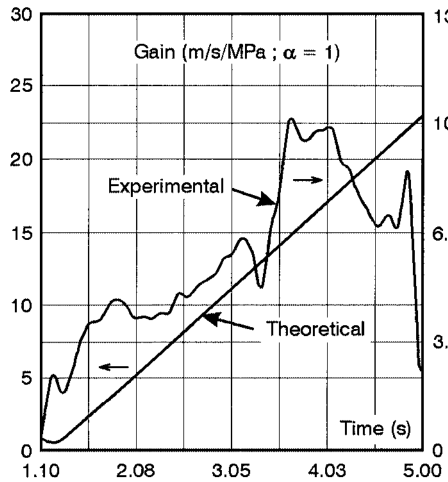

Fig. 12a MHD velocity/pressure gain.

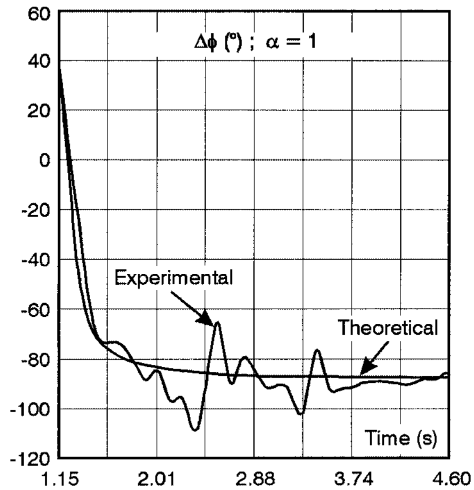

Fig. 12b MHD velocity/pressure phase shift.

Discussion

Direct methods are of great interest but there is a main limitation because of the principle of these methods. Direct methods mean that one is measuring intrinsic parameters, e.g., the propagation-time variation or the complex coefficient of reflection and the strength of the electric field generated by the combustion gases. Thus, this raises the very basic question: What is being measured?

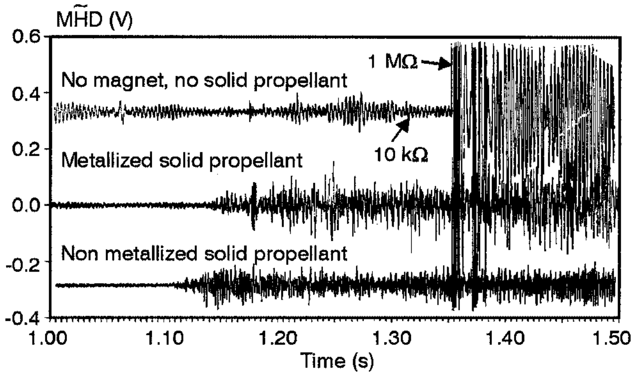

Fig. 13 MHD or thermoelectronic emission effect.

Before looking at the unsteady signal related to the pressure-coupled response, one should examine the steady signal. For MWT, the waves are reflected either on the solid-propellant surface or on the flame position. Of course, the flame stands close to the surface and the gas-phase response time is short compared to the modulation period. This point leads to the definition of the plasma conditions where reflection will occur. This is the position where the sufficient temperature or/and electronic temperature level will exist. The behavior of MWT during mean pressure variations, or after the burnout, could be explained by changes in this position.

MWT is not the only method depending on plasma conditions. The MHD technique is based on a plasma effect giving an electric voltage between the electrodes. The best conditions should be obtained when the electrodes are close to the surface of the solid-propellant grain; but, at this location, the signal has a small amplitude. There is a third method not presented in this paper, which is the plasma capacitance gage technique, which depends strongly on the plasma level.[12,13]

As long as the results obtained for the complete signal from a method are not very well understood, one will not be sure of the method's accuracy or its validity. The burning rate of a solid propellant can be obtained from MWT measurement and it is of significance for the unsteady regime. ULT is devoted mostly to steady burning-rate determination. The analysis of these two methods seems to be accurate enough. For MHD, it is not yet totally proved that the signal obtained is proportional to the velocity inside the chamber. For the solid-phase methods (MWT, ULT), the local conditions affecting the propagation are related only to the solid-phase behavior. The gas-phase method (MHD) is more difficult to interpret because the electrode–gas transfer function is modified by the ionization level of the gas around the electrode ends and deposits of solid particles on the surface of one or two electrodes change the signal voltage much like an impedance load variation.

Unsteady Measurement

Regarding the unsteady measurement, it was seen that, for MWT and ULT, an apparent response function is determined first. Based on theoretical analysis of the measurement, this apparent response is corrected. The MWT corrective terms are small (e.g., cold-flow effect) and can vary with the frequency. ULT method analysis requires a combustion model and the corrective terms significantly influence the final result. Is the unsteady MHD signal sensitive to variations mentioned above or not? What is the thermoelectronic emission effect? This effect alone might be interesting for combustion studies including response function.

Frequency Limit for Direct Methods

The amplitude of the unsteady signals is related drastically to the frequency of the experiment: A frequency limit is reached when the unsteady component amplitude becomes too small compared to the electronic noise. For solid-phase methods, the operating conditions (P'/P over 20%) are usually far from those corresponding to the small-perturbation hypothesis. Thus, concerning measurements through the solid phase, the ULT upper frequency limit stands at 80–100 Hz, and for MWT, this limit goes up to 180–200 Hz. These frequency limits are much too low for the practical response-function range of interest up to 1500 Hz. Thanks to gas-phase velocity amplification, the MHD technique should allow determination of the solid-propellant response in this range.

Conclusions

The aim of future work should be to ensure development of efficient tools for pressure-coupled response-function determination using direct measurement methods. This effort requires an improvement of the understanding of what is being measured. To achieve this objective, tests should be performed on small setups devoted to each measurement method. Direct methods should be coupled two by two on the same burner, but new devices also should be built. Initially, the propellant being tested should be clean, without any particles in its combustion gases. The first step would compare the methods on a homebuilt composite solid propellant. Then, the effects of particles on the results should be studied step by step by including inert oxides or aluminum (size, content). This work also would be helpful for the understanding of the indirect methods.

References

[1]Wilson, J. R., and Micci, M. M., "Direct Measurement of High Frequency Solid Propellant Pressure-Coupled Admittances," *Journal of Propulsion and Power*, Vol. 3, No. 4, 1987, pp. 296–302.

[2]Strand, L. D., Schultz, A. L., and Reedy, G. K., "Microwave Doppler Shift Technique for Determining Solid Propellant Transient Regression Rates," *Journal of Spacecraft and Rockets*, Vol. 11, No. 2, 1974, pp. 75–83.

[3]Russell, L. H., "Burning Velocities of a Solid Propellant via a Microwave Technique at Elevated Pressures and Pressurization Rates," NSWC, TR 79-378, Oct. 1979.

[4]Wood, H. L., O'Brien, W. F., and Dale, C. B., "Measurement of Solid Propellant Burning Rates Employing Microwave Techniques," *Proceedings of the 20th JANNAF Combustion Meeting*, Monterey, CA, Oct. 1983.

[5]Kuentzmann, P., and Traineau, J. C., "Advances in Solid Propellant Pressure-Coupled Response Function Measurement via a Microwave Technique," Nov. 1990.

[6]Tarrin, P., Prévost, M., and Traineau, J. C., "Experimental Low and Medium Frequency Determination of Solid Propellants Pressure-Coupled Response Function," Colloque CNES/ONERA sur le Fonctionnement des Moteurs à Propergol Solide Segmentés pour Lanceurs Spatiaux, Dec. 1992.

[7]Cauty, F., "Measurement of Solid Propellant Response Function at Low Frequency by Means of Ultrasonic Method," *Proceedings of the Conference on Propulsive Flows in Space Transportation Systems*, Vol. 1, Sept. 1995, pp. 101–116.

[8]Cauty, F., "Détermination de la Réponse au Couplage Pression d'un Propergol Solide par Méthode Directe Ultrasonore ($f < 100$ Hz)," ONERA TR 2/6133 EY, Sept. 1988.

[9]Kuentzmann, P., "Modèles de Combustion Instationnaire des Propergols Solides Composites," *La Recherche Aérospatiale*, n°1978-2, pp. 77–93.

[10]Cauty, F., Comas, P., Vuillot, F., and Micci, M., "Magnetic Flowmeter Measurement of Solid Propellant Pressure-Coupled Responses Using an Acoustic Analysis," *Journal of Propulsion and Power*, Vol. 12, No. 2, 1995, pp. 436–438.

[11]Traineau, J. C., Prévost, M., and Tarrin, P., "Experimental Low and Medium Frequency Determination of Solid Propellants Pressure-Coupled Response Function," AIAA Paper 94-3043, June 1994.

[12]Yang, L. C., Miner, E. L., and Romanos, T. C., "Application of Plasma Capacitance Gage (PCG) for Real Time Measurements of Solid Rocket Motor Internal Insulation Erosion," AIAA Paper 90-2327, July 1990.

[13]Seret, J., Démarais, J. C., Cauty, F., and Dupont, M., "Application des Techniques de Mesure d'Épaisseur à la Détermination de la Vitesse de Régression d'une Protection Thermique," Colloque CNES/ONERA sur le Fonctionnement des Moteurs à Propergol Solide Segmentés pour Lanceurs Spatiaux, Dec. 1992, pp. 21/1–23.