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EXPERIMENTAL AND NUMERICAL APPROACH TO THE STUDY OF THE FREQUENCY RESPONSE OF SOLID PROPELLANTS

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Abstract

The experimental study of the frequency response of burning solid propellants has been done using, as external forcing energy source, a CO_2 laser (60 W, 10.6 μm).

The laser radiant flux intensity was sinusoidally modulated and the response of the burning propellant was detected measuring the recoil force generated by the gases coming out from the burning surface using a strain-gage load cell which can operate inside the combustion chamber at the operating pressure. The tests were performed in the sub-atmospheric pressure range and a composite propellant (AP.HTPB/86.14) was used. The combustion chamber was filled by inert gas (N_2) and for each working pressure several tests were carried out at different radiant flux frequency modulations in the range from 5 to 50 Hz. The results evince that the recoil force amplitude depends on the forcing laser frequency with a maximum for every working pressure.

This experimental data set was then used to compare the nonlinear frequency response curves obtained by numerical integration of the combustion model equations. Comparisons between experimental and numerical results at 0.3 and 0.5 atm are shown and the general trend, obtained by numerical simulations, of the propellant frequency response vs pressure in a broader range is presented and discussed.

Introduction

The frequency response study of solid rocket propellants is a peculiar aspect related to the combustion instability problem in the motors. Many theoretical and experimental works were devoted to acquire more detailed knowledge of the phenomenon and many experimental techniques were developed to get data in a wide frequency range [1, 2].

The laser driven combustion technique is the method to influence the solid rocket propellant burning process which has advantages over others. The easiness to control and measure the transient, the possibility to choose different kind of waveforms and the contactless of the method make this equipment very flexible and convenient to be used.

This study, besides the importance to deepen the dynamic behavior of burning propellants, should give further information for the characterization of the composite propellant used in this work. In fact, it is experimentally well defined under steady state configuration [3], in the self-sustained oscillatory combustion regime close to the pressure deflagration limit [4, 5] and during the ignition transients [6—8]. The experimental work is mainly focalized to define, at every working pressure, the frequency for which the burning propellant has the maximum response to the external stimulus and more experimental techniques have been used to confirm the results. The numerical simulations of phenomenon is addressed to reproduce the experimental results to explore broader ranges of pressure and incident flux intensity to define the general trend of the propellant frequency response.

Experimental Apparatus and Procedure

The schematic diagram of the CO_2 laser set up is shown in **Fig. 1.** A stainless steel combustion chamber is collimated with the optical axis of the laser beam. Along the optical line an electro-mechanical shutter, a laser beam analyzer and a power meter are placed. The laser beam comes, through a coated ZnSe window, into the combustion chamber and impinges on the propellant sample (6 mm diameter and 15 mm length) fixed at the load cell which is mounted on a micro $X—Y$ positioning bed to provide convenience in aligning. The CO_2 laser beam (TEM_{00} mode) has a size of 7.5 mm and it is opened operating the shutter. The laser beam analyzer is used to detect the power intensity distribution of the beam and the total power is checked by means of the power meter before and after each test.

Recordings of the burning propellant, by a video system, through one of the two side glass windows, allow to measure the average burning rate [3] and to follow the propellant sample combustion.

Other diagnostic techniques have been implemented to get further data about the propellant burning behavior: Laser Doppler Velocimetry, microthermocouples and photodiode. These ones gave useful results in the study of the self-sustained oscillatory combustion regime [4].

The test procedure consists of filling the combustion chamber by N_2 gas to reach the working pressure, then the power meter is removed from the laser beam line and finally the shutter is operated. Signals generated by the shutter opening, used as trigger of the acquisition systems, and by the load cell are sent to the digital oscilloscope and stored on disk.

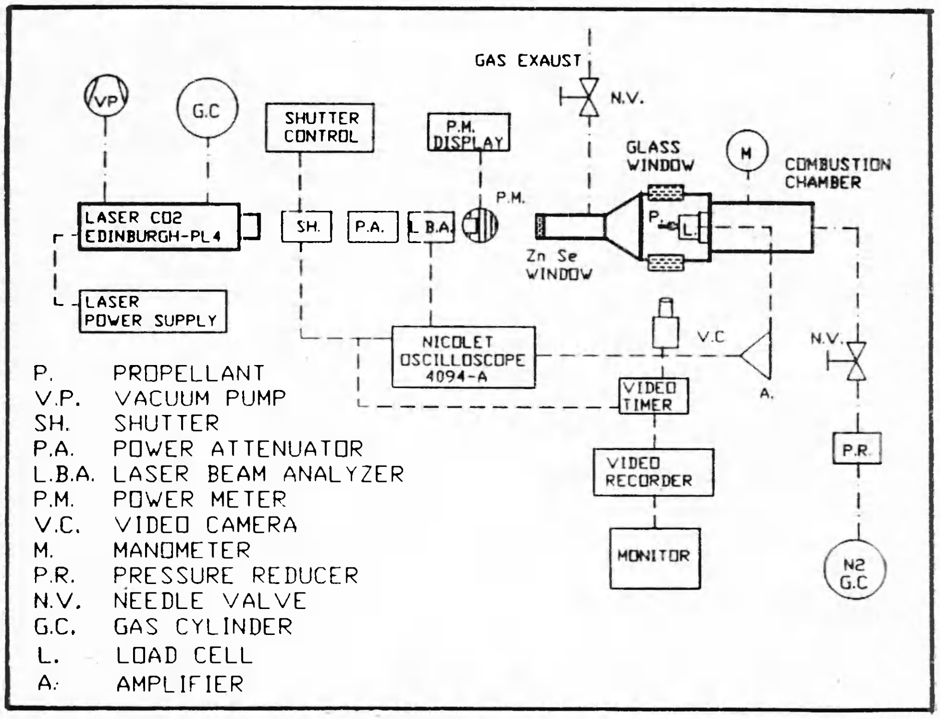

Fig. 1. Experimental apparatus.

Numerical Approach

The 1-D mathematical model is written for a solid propellant cylindrical sample subjected to a sinusoidally modulated radiant flux impinging on the cross section of the propellant. The propellant sample is considered semi-infinite and the reference frame, assumed to write the energy conservation equation, is fixed to the irradiated surface. In such case the equation has to include a term accounting for the convective energy transport due to the relative motion between the propellant and the frame. A scale transformation is used to take into account the steeper gradients in the temperature profile near the burning surface. The scale transformation $x = \exp(\beta x') - 1$ [9] is implemented to map the semi-infinite region $-\infty < x' < 0$ into the finite domain $-1 < x < 0$; β has to be chosen to keep the temperature derivative bounded at $x = -1$. The nondimensional condensed phase energy equation assumes the form:

$$C_c(\vartheta)\left[\frac{\partial\vartheta}{\partial\tau} + R\beta\frac{\partial\vartheta}{\partial x}\right] = \beta^2(x+1)\frac{\partial}{\partial x}\left[K_c(\vartheta)(x+1)\frac{\partial\vartheta}{\partial x}\right] + \frac{F}{\delta_a}(x+1)^{1/\beta\delta_a} \quad (1)$$

where F, the nondimensional external radiant flux intensity, changes in time with a sinusoidal law. To be integrated the equation needs the initial condition: $\vartheta(x, \tau = 0)$-assigned function and the boundary conditions:

$$\vartheta(x = -1, \tau) = \vartheta_a, \quad \left[K_c(\vartheta)\beta\frac{\partial\vartheta}{\partial x}\right]_{c,s} = q_{g,s} + RH_s(x = 0)$$

where $q_{g,s}$ is the nondimensional heat feedback from the gas phase to the burning surface; it is described by means of an appropriate flame model. In this work the KTSS nonlinear flame model [10] is implemented.

The finite difference form of Eq. 1 can be applied to all the grid points, leading to a set of Jf-2 algebraic equations whose coefficients yield a tridiagonal matrix. The Thomas algorithm was used to solve the system.

Results

To face the experimental study of the frequency response it is useful to know the influence on the average burning rate of the radiant flux intensity impinging on the burning propellant surface. This knowledge allows to estimate if the radiant flux intensity variation is large enough (+5—10 %) to get significant burning rate changes without dynamic effects for the burning system and to perform tests at different pressures inducing the same external perturbation to the burning propellant. Results related to these tests indicate that to get the same percentage burning rate increase one has to use higher radiant intensities flux as the operating pressure increases (see Tab. 1).

The data, obtained in the experimental study of the frequency response are processed in order to get, when it is possible, the amplitude of the signal component associated to the forcing frequency. That allows to determine the burning propellant response to the external radiation modulated in the chosen frequency range. Data of the experimental tests and numerical computations are reported in Tab. 2: ΔR is the nondimensional difference between the maximum and the minimum burning rate values while $\Delta R_{\max}$ is larger ΔR in the investigated range. The average flux intensity (I_m) is not the same for the whole data set. The general trend indicated by Tab. 2 is depicted in Fig. 2. This figure is a plot of the resonance frequency vs average flux intensity for different operating pressures. Larger pressure and I_m yield higher resonance frequency and this tendency is physically based on the condensed phase characteristic time decrease with the pressure and/or the I_m increase.

TAB.1

Flux intensity increment to get the same steady burning increase at different working pressure when the incident flux intensity is 5 cal/cm^2 s

P [atm]	Δ_{rb} = 2.5%	Δ_{rb} = 5%	Δ_{rb} = 10%	Δ_{rb} = 15%
	ΔI_0%	ΔI_0%	ΔI_0%	ΔI_0%
0.1	10	20	36	55
0.5	20	40	72	100
1	34	60	100	135

TAB.2

Dependence of the amplitude ratio ΔR/ΔRmax on the forcing frequency Numerical and experimental results.

f [Hz]	ΔR/ΔRmax					
	0.3 [atm]		0.5 [atm]		0.9 [atm]	5 [atm]
	num	exp	num	exp	num	num
2	0.78	0.39	0.65	0.48	0.63	——
8	1	0.82	——	0.65	——	——
10	0.98	1	0.95	0.71	0.90	0.55
15	0.91	0.84	1	——	——	0.58
20	0.83	0.62	0.97	0.90	0.99	——
25	——	——	0.91	1	1	0.70
30	0.68	——	0.83	0.94	0.98	——
50	——	——	——	——	——	0.82
100	0.34	——	0.43	——	0.62	0.94
150	——	——	——	——	——	0.99
200	——	——	——	——	0.51	1
600	——	——	——	——	——	0.67
Im [cal/cm^2 s]	2	5	0.3	6	0.5	5

Conclusions

The solid propellants combustion driven by laser radiation applied to the study of the frequency response of burning propellants is a method which allows to work at constant pressure of the combustion chamber avoiding some pressure coupling.

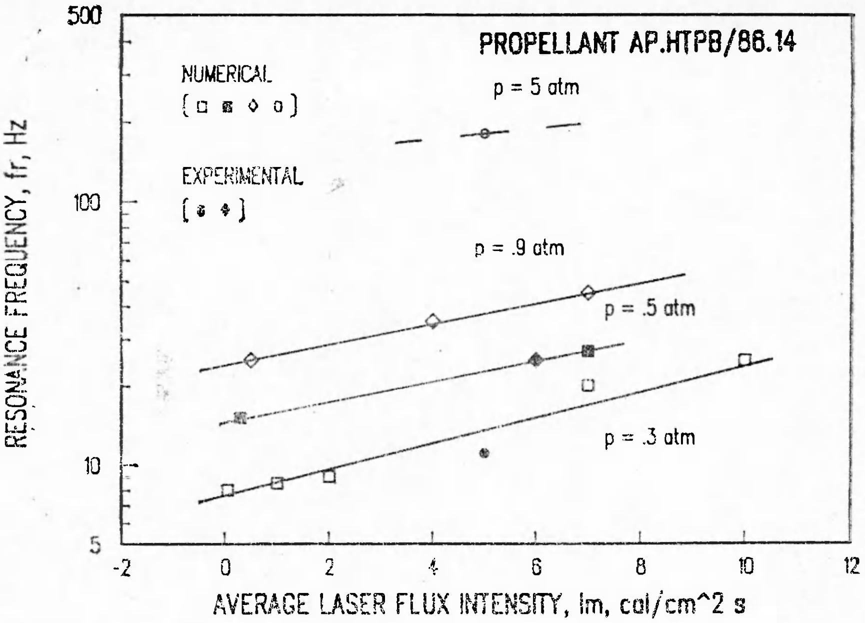

Fig. 2. Resonance frequency vs incident flux intensity for AP.HTPB/86.14 propellant at different working pressure.

The experimental diagnostic techniques used to study the frequency response of burning propellant has given reasonable results in the subatmospheric pressure range. The more reliable one is the method to measure the recoil force generated by the gas coming out from the burning surface because by means these results is possible to evaluate the instantaneous burning rate. The tests carried out at different operating pressure have pointed out that at every pressure a frequency exists for which the burning propellant has its larger response and that this value increases with the pressure increase. The numerical simulation has shown that the data set, experimentally obtained, is suitable to the unsteady burning propellant description and the results well compare with the experimental data and give the possibility to explore the propellant frequency response in a wide pressure range.

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СПОСОБ ОПРЕДЕЛЕНИЯ ОТКЛИКА СКОРОСТИ ГОРЕНИЯ ТОПЛИВА НА ИЗМЕНЕНИЕ ДАВЛЕНИЯ С ПОМОЩЬЮ ИЗЛУЧЕНИЯ

В рамках феноменологического подхода Зельдовича — Новожилова рассматривается возможность получения функции отклика с помощью излучения и с последующим пересчетом в функцию отклика по давлению. Предложена методика непосредственного получения вида нестационарного отклика скорости горения по давлению из экспериментов по горению топлива при действии специальным образом модулированным излучением.

До сих пор экспериментально определять закономерности поведения нестационарной скорости горения твердых топлив при изменении давления достаточно сложно. В связи с этим весьма заманчивым выглядит способ получения таких закономерностей с помощью воздействия излучением на процесс горения с последующим пересчетом результата в отклик скорости по давлению. Теоретически такая возможность показана в работе [1] на примере функций отклика по давлению и излучению для модели горения с квазистационарными зонами химических реакций в газовой и конденсированной (в бесконечно узком поверхностном слое) фазах. При этом важно условие поглощения излучения на поверхности топлива. В этом случае обе функции отклика совпадают с точностью до коэффициента. В [2] уточнено, что результат справедлив только при достаточно малом среднем уровне мощности излучения.

В рамках феноменологического подхода Зельдовича — Новожилова [3], в котором сформулирована наиболее общая формулировка квазистационарного метода в теории нестационарного горения твердых топлив, поведение скорости горения описывается уравнением теплопроводности в к-фазе с соответствующими граничными и начальными условиями

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} = \varkappa\frac{\partial^2 T}{\partial x^2}, \quad -\infty < x < 0, \tag{1}$$

$$u = u^0(T_s - \varkappa\varphi/u,\ p,\ q), \tag{2}$$

$$T_s = T_s^0(T_s - \varkappa\varphi/u,\ p,\ q), \tag{3}$$

$$\varphi = \left.\frac{\partial T}{\partial x}\right|_{x=0}, \quad p = p(t),$$

$$q = q(t), \quad T(x,\ 0) = T_0(x).$$

Здесь T — температура к-фазы; u — скорость горения; t — время; x — пространственная координата; p — давление; q — поглощающееся на поверхности излучение; $\varkappa$ — температуропроводность. Индекс s соответствует поверхности, индекс нуль вверху — стационарным условиям, внизу — начальным.

Прообразы нестационарных зависимостей (2), (3) — стационарные функции $u^0(T_0,\ p,\ q)$, $T_s^0(T_0,\ p,\ q)$. Функция отклика (продукт ли-