10o Brazilian Congress of Thermal Sciences and Engineering -- ENCIT 2004
Braz. Soc. of Mechanical Sciences and Engineering -- ABCM, Rio de Janeiro, Brazil, Nov. 29 -- Dec. 03, 2004

ACOUSTIC CAVITIES DESIGN PROCEDURES

Mariana de Sousa Silva
Instituto Tecnológico de Aeronáutica, Departamento de Propulsão
Pça. Mal. Eduardo Gomes 50, São José dos Campos – SP, 12228-900
msilvafts@yahoo.com

Avandelino Santana Junior
Instituto de Aeronáutica e Espaço, Divisão de Sistemas Espaciais
Pça. Mal. Eduardo Gomes 50, São José dos Campos – SP, 12228-900
santanajr@iae.cta.br

Pedro Teixeira Lacava
Instituto Tecnológico de Aeronáutica, Departamento de Propulsão
Pça. Mal. Eduardo Gomes 50, São José dos Campos – SP, 12228-900
placava@ita.br

Luiz Carlos Sandoval Góes
Instituto Tecnológico de Aeronáutica, Departamento de Projetos
Pça. Mal. Eduardo Gomes 50, São José dos Campos – SP, 12228-900
goes@ita.br

Abstract. *Combustion instability is recognized as one of the major problems frequently faced by engineers during the development of either liquid or solid propellant rocket engines. The performance of the engine can be highly affected by these high frequencies instabilities, possibly leading the rocket to an explosion. The main goal while studying combustion chambers instability, either by means of baffles or acoustic absorbers, is to achieve the stability needed using the simplest possible manner. This paper has the purpose of studying combustion chambers instabilities, as well as the design of acoustic absorbers capable of reducing their eigenfrequencies. Damping systems act on the chamber eigenfrequency, which has to be, therefore, previously known*

Keywords*. Combustion instability, liquid propellant rocket engine, instability control in rocket engines*

1. Introduction

Combustion instability is recognized as one of the major problems frequently faced by engineers during the development of either liquid or solid propellant rocket engines. The performance of these engines can be highly affected by high frequencies instabilities, possibly leading the rocket to an explosion.

Although the problem has been unceasingly studied for the past four decades, no theoretical general rules have yet been established for designing stable combustor systems. Therefore, concerns on combustion instabilities are still present in every chamber design; the sooner this problem is detected during the development phase, the smaller are the additional expenses with delays in the project.

Combustion instability results from a coupling of the combustion process and the fluid dynamics of the engine system. By this coupling, the combustion process delivers energy to pressure and velocity oscillations in the combustion chamber. So, combustion instability can be severely mitigated or even eliminated by reducing the coupling of these oscillations, or also, by increasing the engine system damping. This can be achieved by means of the use of baffles or acoustic absorbers. Baffles are believed to reduce coupling, while acoustic absorbers are assumed to increase damping.

The main goal while studying combustion chambers instability, either by means of baffles or acoustic absorbers, is to achieve the stability needed using the simplest possible manner (Culick, 1995 and Flandro, 2002).

With the purpose of studying combustion chambers instabilities, this paper presents the design of acoustic absorbers, which act on the chamber as damping systems, reducing the amplitude of a given eigenfrequency and, for that reason, resonant frequencies must be known previously.

Since the discussion of acoustic absorbers (and baffles as well) will make frequent references to the acoustic of combustion chamber, a short discussion of classical acoustics at the next section will be proven helpful in understanding subsequent experimental procedures and results.

2. Theoretical Introduction

Acoustic resonators and baffles are damping devices successfully used to reduce or even eliminate oscillations caused by combustion instability. Resonators are narrowband absorbers that must be tuned accurately to discrete acoustic eigenfrequencies of the combustion chamber. Thus, these frequencies should be known at the beginning of laying out resonating cavities, and they may be determined using cold-test results, for example.

Baffles can affect drastically configuration of an existing engine. The use of them necessitates discontinuities in injection patterns, which produces irregularities in the combustion-product flow field and therefore produce poor performance. That is the reason why baffles interact directly with injector and chamber design.

Acoustic absorbers, on the other hand, are assumed to increase the damping in the engine system. The acoustic liners, series of acoustic absorbers one beside another sharing the same resonator volume, have a damping effect because they allow a normal velocity at the wall which has a component in phase with the pressure oscillation; this means that work is done over each cycle in moving the fluid back and forth at the boundary. This work is equal to the energy dissipated due to friction.

2.1. Resonant Frequencies

Resonant frequencies or eigenfrequencies of a vibrating object are those frequencies for which stationary waves are present inside the object. Stationary waves result from the interference of two different waves in opposite directions; stationary waves that correspond to eigenfrequencies are the ones that persist for longer times.

Acoustic tests with models have shown that the combustion chamber and nozzle configuration must be treated theoretically as a closed/closed system. Therefore, the eigenfrequencies for a cylindrical chamber closed at both sides can be calculated with Eq. (1):

$$f_{m\,n\,q} = c\sqrt{\left(\frac{b_{m\,n}}{D_{ch}}\right)^2 + \left(\frac{q}{L_{ch}}\right)^2} \quad , \qquad (1)$$

$b_{m\,n}$ - transversal eigenvalue;
q – longitudinal eigenvalue;
D_{ch} - chamber diameter;
L_{ch} - chamber length;
c - velocity of sound.

2.2. Baffles

Injector-face baffles, as depicted on Fig. (1), are intended for working as damping devices at high frequency modes of instability as the transverse modes. These modes of instability are characterized by oscillations parallel to the injector face. The stabilization effects identified with regard to the transverse mode instability by injector-face baffles are:

(i) the modification of the acoustic properties of the combustion chamber;

(ii) restriction of the oscillatory flow patterns between baffle blades, thus protecting the sensitive pre-combustion processes;

(iii) damping of the oscillations by vortex generation, separation or frictional effects.

One of major concern in the design of an effective baffle is the location of the blades and hubs relative to particle paths, since the baffle constitutes an obstruction to particle motion.

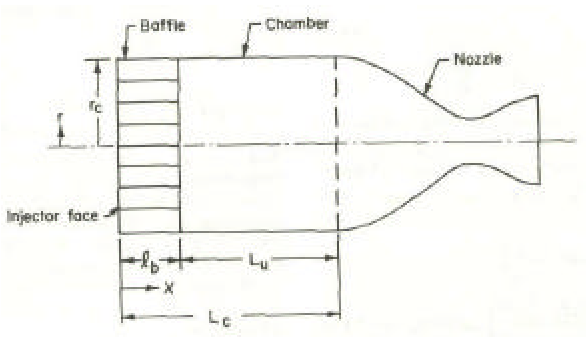

Figure 1. Combustion Chamber with a baffle

Unfortunately, the state-of-the-art of baffle design is such that no argument can be presented to prove conclusively that only one dominant mechanism exists. Hence, in the design of an effective blade arrangement the selection of compartment size, blade length, number, position and degree of symmetry may follow different paths of logic. Refer to Harrje and Reardon for detailed information on this matter.

2.3. Acoustic Cavities

One type of existing acoustic cavities is a Helmholtz resonator, Fig. (2). The theory of Helmholtz resonators was first treated mathematically by Helmholtz in 1860 and was afterwards simplified by Lord Raleigh. Since then, they have been extensively used as sound filters, noise suppression, in the suppression of combustion instabilities and nowadays, as damping devices for unstable liquid-propellant rocket engines. Basically, it consists of a small passage connecting the combustion chamber to a resonator cavity; the cavity dimensions are large compared with the passage width, but small compared with a wavelength.

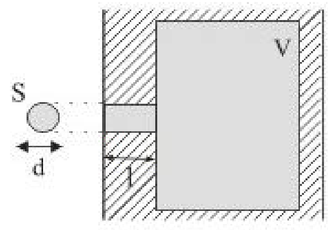

Figure 2. Helmholtz resonator

If the dimensions of the various resonator elements are small in comparison to the wavelength of the oscillation, the gas motion behavior in the resonator is analogous to a mass-spring-dashpot system. From the geometrical dimensions, the undamped resonant frequency may be calculated by Eq. (2) as it follows:

$$f_0 = \frac{c}{2\,p}\sqrt{\frac{S}{V\left(l+\Delta l\right)}} \tag{2}$$

S – orifice area;
V – cavity volume;
Δl - length correction (about 0.85d for lower noise levels);
c - velocity of sound.

To study the acoustic behavior of the resonators, their acoustic impedance *Z* must be determined. The acoustic impedance of a volume is a complex unit consisting of the sum of an acoustic resistance (*R*) and an acoustic reactance (*X*). For a resonator, the acoustic impedance can be separated between the cavity and the aperture impedance, resulting in Eq. (3), as it follows:

$$Z = Z_c + Z_A = \left(R_C + R_A\right) + i\left(X_C + X_A\right). \tag{3}$$

For a Helmholtz resonator, it follows that:

$$Z = R_A + i\left(X_A + X_C\right); \tag{4}$$

where,

$$X = X_A + X_C = \bar{r}_A w_0 l_e\left(\frac{w}{w_0} - \frac{w_0}{w}\right); \tag{5}$$

$$R_A = \Gamma\ \bar{r}_A\ \hat{u}_A; \tag{6}$$

and,

$$w_0 = \left(\frac{g_A\, \overline{P}_A}{\overline{r}_A} . \frac{A_A}{l_e\, V_C} \right)^{1/2} = c_A \left(\frac{A_A}{l_e\, V_C} \right)^{1/2} . \tag{7}$$

V_C - volume of cavity;

g_A - ratio of specific heats of gas in the aperture;

w - angular frequency of oscillation;

A_A - cross-sectional area of aperture;

$\overline{r}_A$ - time-averaged gas density in the resonator open end;

$\hat{u}_A$ - peak velocity amplitude in the open end;

Γ - coefficient that varies with resonator type. For Helmholtz resonator, $\Gamma = 0{,}37/c_1^2$.

l_e - effective aperture length, given by $l_e = l + d$, i.e., the addition of the physical length (l) to the length end correction (d), given by $d = 0{,}96\, A_A^{1/2} \left(0{,}5 - 0{,}7\, \sqrt{a} \right)$ for low area ratios resonators (*a* = aperture area / resonator area).

Acoustic absorber may be comprised of either a large number of resonators distributed along the thrust chamber wall from injector to the beginning of nozzle convergence or, conversely, a limited number of resonator used over a limited portion of the chamber, usually along the injector plate, as it is shown on Fig. (3). Acoustic liners are important damping devices: energy is dissipated on account of the jet formation in the flow through the liner orifices. In liner design, various factors must be considered which include environmental factors sizing of the resonators and the number and placement of these resonators.

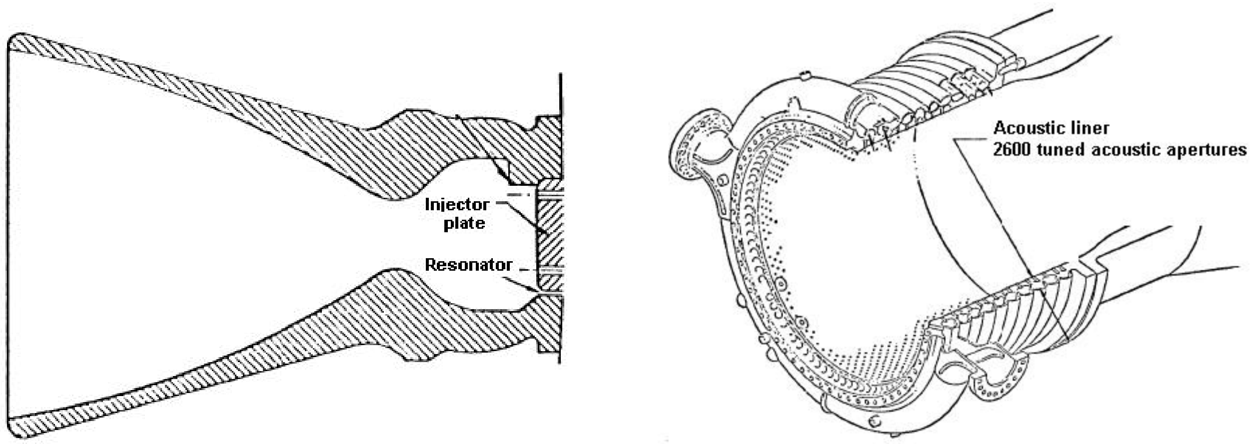

Figure 3. Position of Helmholtz resonators and acoustic liner along combustion chamber

As previously stated, in order to study the acoustic behavior of the resonators, their acoustic impedance Z must be determined, what can be done using the equations given above, from Eq. (3) through (7). These values are used in the evaluation of the absorption and conductance coefficients, which are employed in the analyses of the acoustic behavior of resonators.

2.4. Absorption Coefficient

It is one of the most widely used measures of full-length liner effectiveness. It is defined as the fraction of the oscillatory energy incident on a wall that is absorbed at the wall, as it follows:

$$a = \frac{4R/e\, r\, c}{\left[\left(1 + \frac{R}{e\, \overline{r}\, c} \right)^2 + \left(\frac{X}{e\, \overline{r}\, c} \right)^2 \right]} ; \tag{8}$$

e - fraction of surface with acoustic impedance *Z*;

$\bar{r}$ - time-averaged gas density in chamber;

c - sound speed in chamber.

2.5. Conductance

The conductance (real part of the resonator admittance) is evaluated as shown in Eq. (9). It is known as the power loss factor and thus, should be considered together with the absorption coefficient when optimizing the system's damping.

$$x = \frac{R/_{e\ r\ c}}{\left[\left(\frac{R}{e\ \bar{r}\ c}\right)^2 + \left(\frac{X}{e\ \bar{r}\ c}\right)^2\right]}. \qquad (9)$$

3. Method

As described by Laudien et al, acoustics tests were carried out using a full-scale combustion chamber model, as shown in Fig. (4). This study had the purpose of analyzing one particular configuration of combustion chamber, obtaining its eigenfrequencies, as well as any other possible critical frequencies, which could be present.

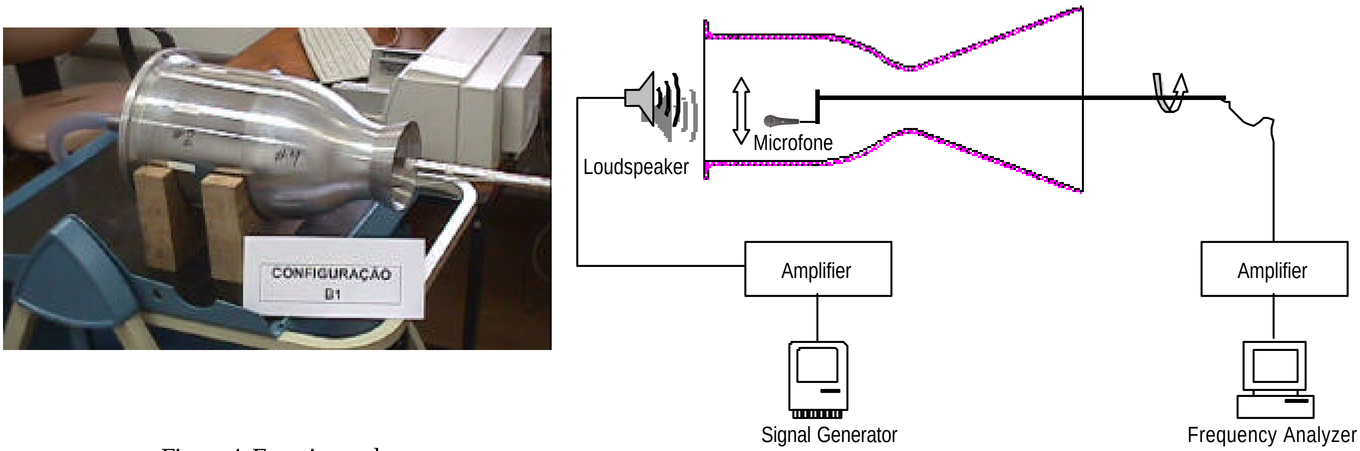

Figure 4. Experimental setup

The model chamber was equipped with small loudspeakers in the injector faceplate. A microphone mounted on a rod was attached to a tube, making it possible to reach different positions within the chamber. Random noise was used as the source for the loudspeakers. Resonant frequencies in the chamber were identified by registering microphone signals throughout the chamber. Once the frequencies were known, a sine generator was used to activate only one particular mode. The shape pattern of the mode was then determined by scanning the chamber in azimutal and/or radial and axial directions for nodal lines. These lines of minimum pressure can be found, first, by observing the amplitude and, second, by locating any phase shift in the chamber. The latter is accomplished by comparing the phase between the measured signal and a reference signal taken directly from the loudspeaker. Each time the microphone moves through a nodal line, the acoustic pressure will be at a minimum and the phase will shift by 180 deg.

The spectrum of the test performed in air under ambient conditions used in the following discussions is presented in Fig. (5) and corresponds to the longitudinal and transverse modes. The configuration of the chamber used in these tests is shown in Fig. (6).

Figure (5) represents the spectrum of an acoustic test, which the "white noise" was generated by signal generator and the microphone was at given position inside chamber (x, r, q).

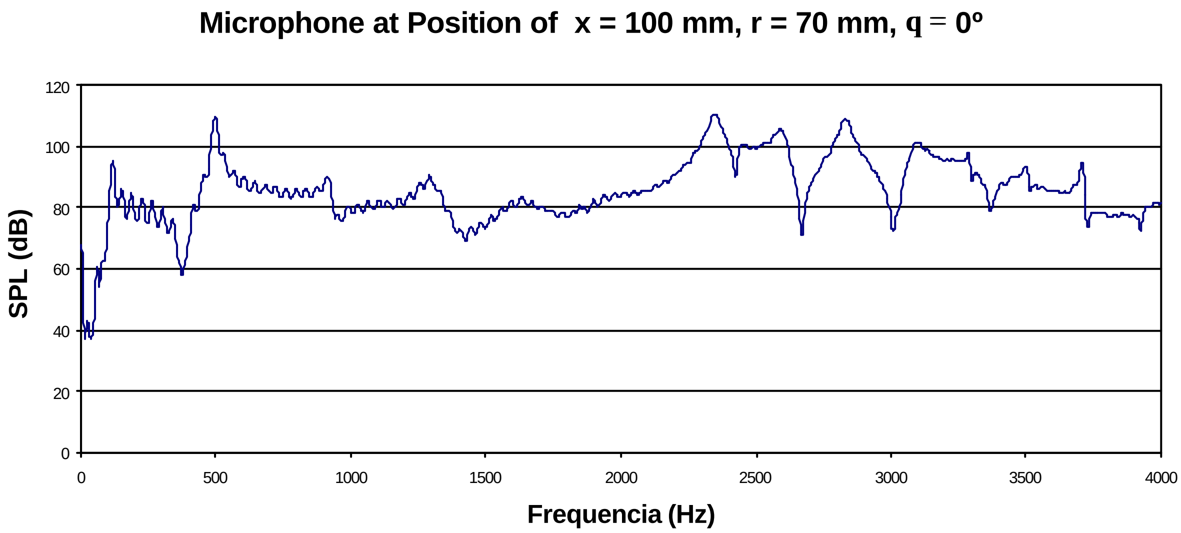

Figure 5. Frequency spectrum measured in a combustion chamber model under cold-gas condition.

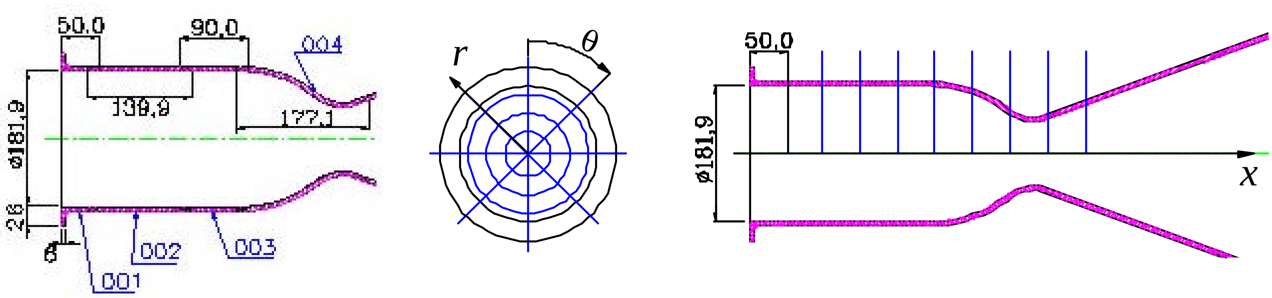

Figure 6. Configuration of the combustion chamber (lengths in mm) and possible positions of microphone (*x*, *r*, *q*)

The main study was based in the highest SPL (Sound Pressure Level) noticed during the experiments, namely, 500 Hz. Initially, a Helmholtz resonator was designed as to be effective against this particular eigenfrequency, through a compromise among its volume, aperture length and diameter, according to Eq. (2). The resonator so designed was put together with others of the same nature as to form liners, containing several rows, each with an average of 60 apertures. The absorption coefficient (Eq. (8)), when evaluated for combustion chambers equipped with different numbers of rows in the liner, allows conclusions over the damping efficiency of the system.

Another study, which carried out, refers to the bandwidth in which the resonator is effective. Designing a specific type of resonator for a configuration with an unknown eigenfrequency is not advisable. In these cases, the increase of the bandwidth as a result of the presence of a larger number of resonators may be desirable in order to increase the system's damping.

Evaluation of the absorption coefficient involves the calculation of the acoustic impedance through Eq. (3). Then, considering the acoustic tests carried out in combustion chamber full-scale models as the one in Fig. (5), the eigenfrequency is determined and later used in Eq. (2), along with given aperture length and diameter, to determine the cavity volume. This volume is then multiplied according to the number of apertures that are considered (number of rows within a liner times 60, which is the number of apertures in each row, as previously stated) and used in Eq. (3) to (7) along with flow (air) properties with the purpose of evaluating α (absorption coefficient) and ξ (conductance).

4. Results

Three different configurations concerning the number of aperture rows in the liner placed on the first section of the combustion chamber were studied under the approach of the absorption coefficient and the conductance. The first configuration was chosen as to lead to an *under damped* system; then, the number of rows in the liner was increased and the resulting absorption coefficient graphic observed. At certain point in this procedure, a particular configuration was such that increasing its number of rows did not increase the system's absorption coefficient anymore. So, this configuration was named as the one to produce an *optimized damped* system. In this presentation, this configuration was found to have seven rows of apertures (420 apertures). Then, as previously explained, an increase in the number of rows within a liner led to a decrease in the absorption coefficient; however, an increase in the bandwidth of the absorption coefficient was also found, that is, the configuration was effective over a larger amount of frequencies. A configuration containing 20 rows of absorber apertures was chosen to show these aspects within the following graphics.

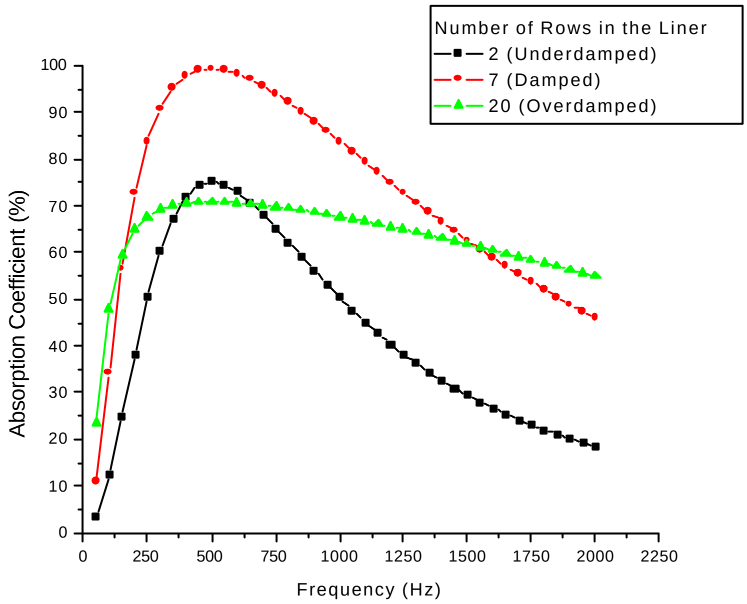

Figure 7. Absorption Coefficient behavior of an under-, optimized-, and overdamped system

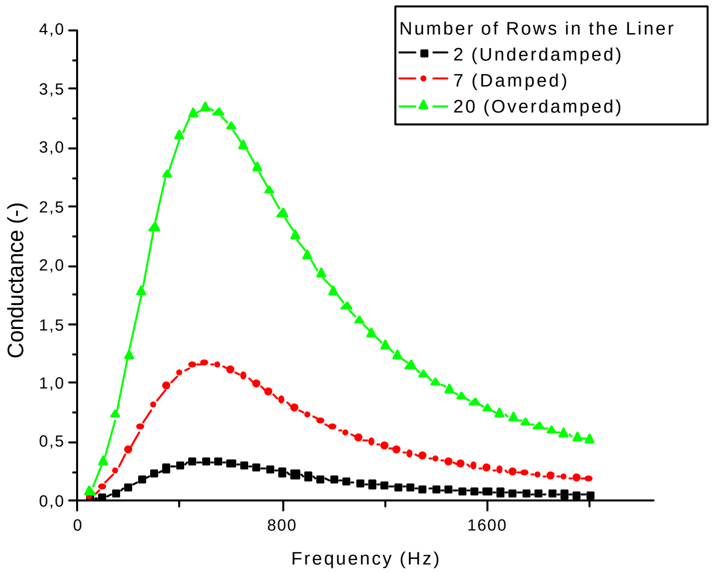

Figure 8. Conductance behavior of an under-, optimized-, and overdamped system.

The number of rows considered in the figures above were chosen as to produce the desired damping characteristics (under-, optimized-, and over damped), as explained above. Several observations can be made concerning this behavior. Initially, whereas the absorption coefficient has it optimum at 100% (no reflection of sound intensity at the chamber wall), the conductance term is not limited by definition (Fig. (8)). In this example, optimizing the system's damping by means of the absorption coefficient would suggest a 7-row liner (Fig. (7)). However, the conductance term suggests the overdamped configuration. It is also important to notice that this particular configuration increases the bandwidth.

Considering the bandwidth, the resonator configuration can be made as to provide the highest bandwidth instead of providing the maximum absorption for a given eigenfrequency. Considering the main SPL peaks shown in Fig. (5), analyze the acoustic resonators designed to damp these frequencies (considering a 2-row configuration).

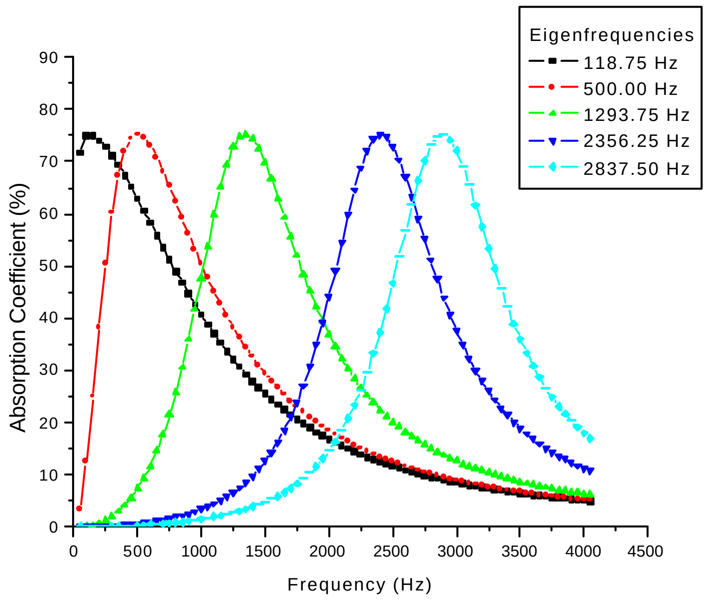

Figure 9. Absorption Coefficient for different eigenfrequencies.

It is clear now (Fig. (9)) that increasing the absorption coefficient requires the variation of the number of resonators (in the present study, this is accomplished by increasing the number of rows of resonators in a liner), as well as increasing the bandwidth. Therefore, consider the configurations in Fig. (10).

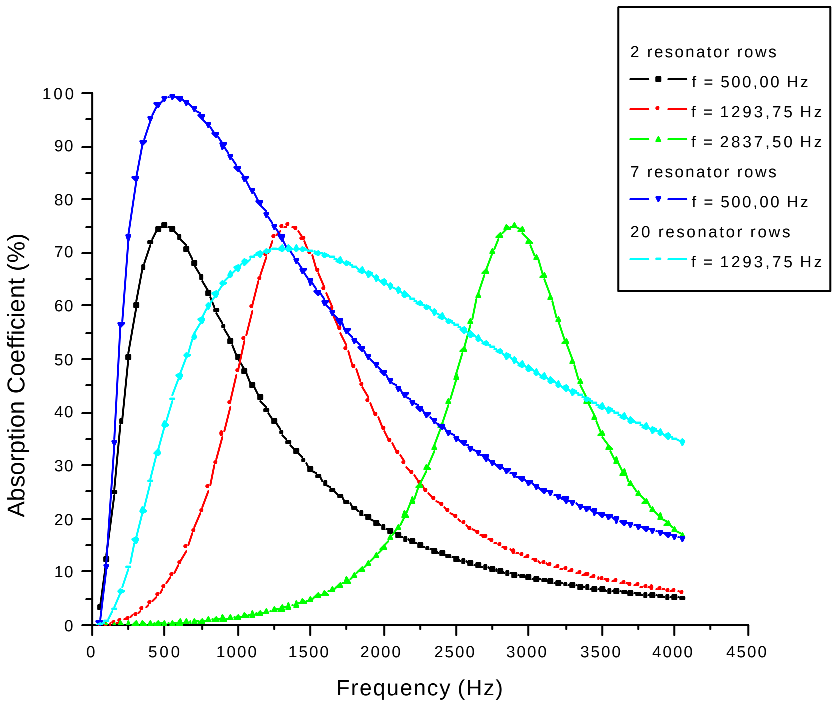

Figure 10. Absorption Coefficient Comparation

In the search for an optimized configuration, Fig. (10) points out to a configuration designed for a 1293,75 Hz frequency, which does not correspond to a peak in Fig. (5). However, one can notice that the bandwidth is highly increased, keeping high absorption coefficients even at larger frequencies.

5. Conclusions

Several experimental approaches have been made in the search for a practical way of predicting and eliminating instability of combustion chambers. The most effective of them to stabilize rocket engines have been found to be either removing energy from the oscillation or preventing certain modes of oscillations by means of stabilization devices. The use of resonators has been demonstrated to be most simple.

Helmholtz resonators have been extensively used as sound filters, noise suppression, in the suppression of combustion instabilities and nowadays, as damping devices for unstable liquid-propellant rocket engines.

Acoustic liners are important damping devices: energy is dissipated on account of the jet formation in the flow through the liner orifices. In liner design, various factors must be considered which include environmental factors sizing of the resonators and the number and placement of these resonators.

The preceding discussions leads to conclusions among which features that acoustic tests in air under ambient conditions with full-scale chamber models are important in the design of resonators. Also, the absorption coefficient cannot be analyzed alone when it comes to the specification of the optimized resonator configuration -the conductance term should also be analyzed. The maximization of this coefficient must be done by selecting the right number of resonators within the absorber arrangement. The overdamped configuration proved itself to be ideal for the analyzed case, concerning both the absorption coefficient and the conductance.

This paper is basically a theoretical study of the behavior of a combustion chamber provided with acoustic resonators to prevent oscillations. It is not complete, given the fact that experimental tests must be carried out in order to confirm (or even refute) the discussions made. Therefore, this work is just an attempt to better understand the theoretical behavior of resonators treated as acoustic devices.

6. References

Culick, F.E.C, 1995, (California Institute of Technology) & Yang, V. (Pennsylvania State University), "Overview of Combustion Instabilities in Liquid-Propellant Rocket Engines", in: "Liquid Rocket Engine Combustion Instability", AIAA.

Flandro, G., 2002,"Combustion Instability: Analysis, Diagnosis and Corrective Procedures".

Harrje, D. T. and Reardon, F. H., 1972, "Liquid Propellant Rocket Combustion Instability". NASA SP-194.

Laudien, E., Pongratz, R., Prelick, D., 1995, DASA, "Experimental procedures Aiding the Design of Acoustic Cavities", in: "Liquid Rocket Engine Combustion Instability", AIAA.

NASA SP-8113, 1974, "Liquid Rocket Engine Combustion Stabilization Devices".