DYNAMIC CHARACTERIZATION OF A LIQUID PROPELLED ROCKET COMBUSTION CHAMBER

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Abstract. *On the design of combustion chambers for liquid and solid propelled rocket the presence of acoustic modes is an important feature to be considered. These modes can cause instabilities on the burning process and should be well known during the design stage. An acoustic cavity simulating a combustion chamber was analyzed by the finite element method and the results are compared to experimental results. The effect of placing Helmholtz resonators into the chamber is also analyzed.*

Keywords*: Acoustic modes, Finite Elements, Combustion chamber instability*

1. Introduction

Combustion instability is the interaction of the combustion chamber acoustic modes with the combustion process and/or fluid dynamic processes. The phenomena can be observed in a power spectrum of the pressure signal of a combustion chamber (Bunrley and Culick 1997). When the combustion instability occurs, sound pressure peaks summed to the background noise appears (Pirk et al, 2005).

This kind of instability can affect the rocket's performance and so it is important to make some preliminary studies of the combustion chamber acoustics, calculating and/or measuring the acoustic modes. By doing so, one can optimize the combustion chamber's configuration to avoid or to minimize the effect of combustion instability.

As a part of the IAE efforts on the development of liquid propulsion systems, in this work the finite element method is used to calculate the acoustic modes of a combustion chamber prototype. The numerical results are compared to the ones obtained by experimental data. In another chamber model we use the same method to study the influence of a Helmholtz resonator on the acoustic modes. It is important to mention that the analysis and tests were performed under the environmental conditions of the air, without simulating the pressure and temperature conditions during the combustion of a rocket engine.

2. Acoustic modelling by the finite element method

The finite element method is commonly used on the analysis of solid structures and can also be used on the modeling of acoustic cavities. The calculation of acoustic modes is very similar to the eigen analysis performed in structural dynamics.

The equations governing the acoustic system are derived using pressures as nodal variable and the problem can be discretized using the standard finite element method. Using the interpolation functions ($[N_f]$) one can write the pressures by (Zienkiewicz and Taylor, 1994):

$$p = [N_f]\{p_n\} \tag{1}$$

where $\{p_n\}$ is the nodal pressure vector.

A fluid domain at rest, considered inviscid, homogeneous, with no-rotational flow is governed by the Helmholtz equation. Assuming the conditions cited above and a fluid domain limited by rigid non absorbing walls, the Helmholtz equation can be discretized and the kinetic energy ($\boldsymbol{T_f}$) and potential energy ($\boldsymbol{U_f}$) could be write in the following form :

$$\boldsymbol{T_f} = \tfrac{1}{2}\{p_n\}^T[H]\{p_n\} \tag{2}$$

$$\boldsymbol{U_f} = \tfrac{1}{2c^2}\{\dot{p}_n\}^T[E]\{\dot{p}_n\} \tag{3}$$

Where [*E*], [*H*] are the compressibility and the volumetric matrices respectively and ρ_f is the fluid specific mass. Considering the free vibration's case for small oscillations and applying Lagrange's equations leads to:

$$[E]\{\ddot{p}_n\}+[H]\{p_n\}=\{0\} \tag{4}$$

3. Practical example

The combustion chamber prototype analyzed is described in the Fig.1.

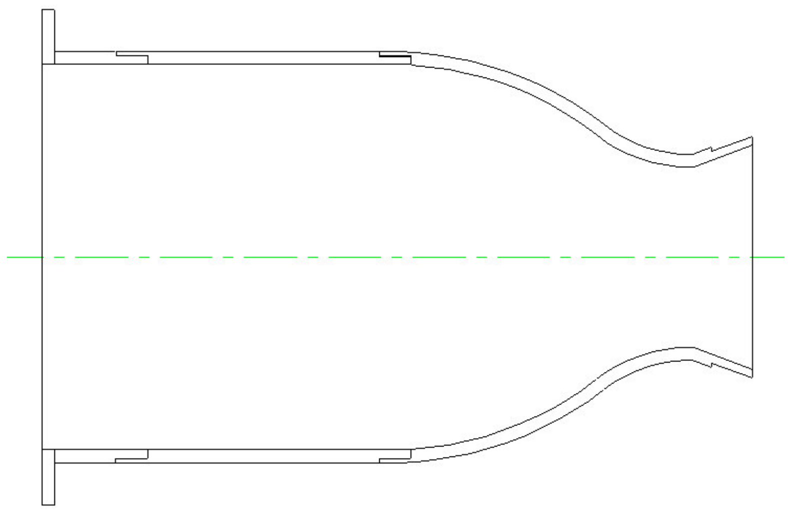


Figure 1 – Combustion chamber analyzed

The finite element model of the chamber was built using the commercial finite element code ANSYS (ANSYS, 1994). The mesh used in the analysis is shown in Fig. 2. The fluid properties (air) are: ρ =1.225 Kg/m^3 (specific mass) and c=340m/s (sound velocity). As boundary conditions all surfaces were considered rigid walls excepted by the nozzle throat where zero nodal pressures were imposed to represent an open cavity (Zienkiewicz and Taylor, 1994). Linear hexahedral elements were used and the whole model has 24358 degrees of freedom.

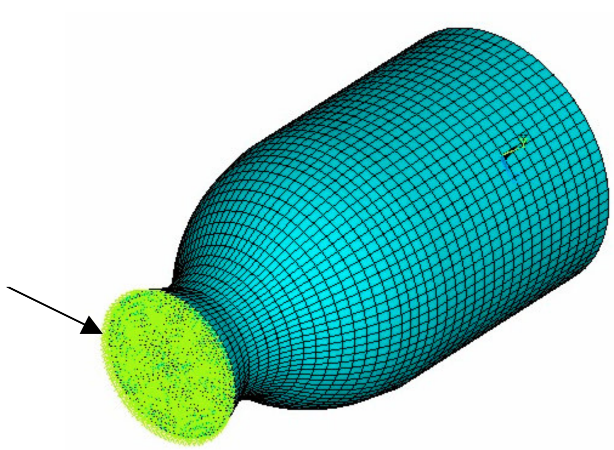


Figure 2 – Combustion chamber mesh

The bigger element in the mesh has 0.03241 m as its bigger dimension. Assuming 10 elements per wave length, this corresponds to a wave length of 0.3241 m and follows that the frequency band analyzed precisely by the finite element model goes from 0 to 1049 Hz.

3.1 Measurement of acoustic parameters

To measure the acoustic modes the set up show in Fig. 3 was used. On these experimental investigations, the combustion chamber configurations were equipped with an external noise source, installed at the injection faceplate of the chamber, which injected the excitation noise inside the chamber. An excitation signal was generated by a signal generator, which provided a white noise (0 to 20 kHz) to be injected by the noise source. However, due to the manufacturing characteristics of the acoustic source, the injected noise frequency band was from 400 Hz to 20 kHz. The measured acoustic pressure levels were registered by using a digital analyzer, for posterior analysis.

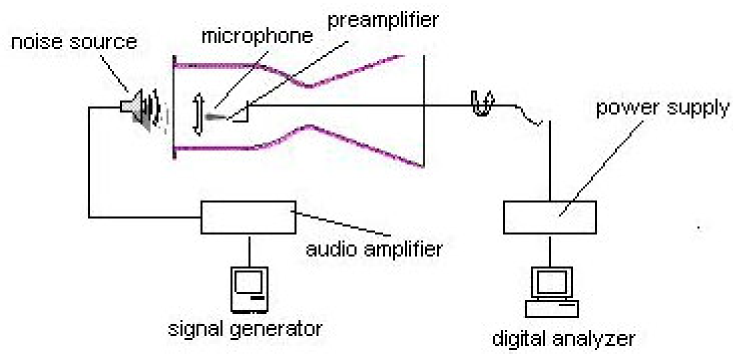


Figure 3: Measurement set up

The acquired Frequency Response Functions (FRF), describe the acoustic response of the fluid media due to the external acoustic excitation. These FRF were captured by a ¼" capacitive pressure microphone, which was mounted on a thin rod, and with which it was possible to reach all the measurement positions axial, azimuthal and radial, in the chamber inner environment. This microphone was conditioned by power supply and preamplifier to measure the sound pressure level inside the combustion chamber, when it is subjected to an external acoustic excitation. See Fig.4.

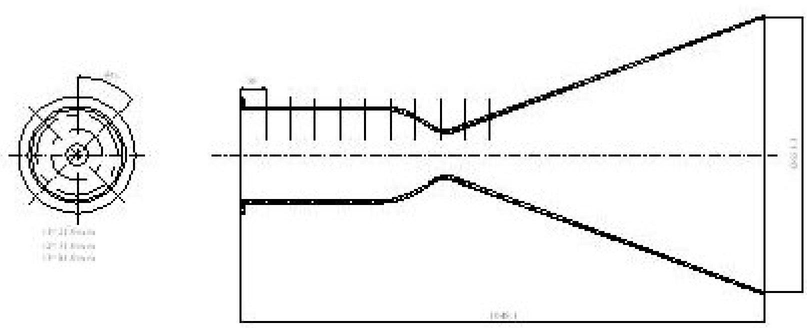


Figure 4: Microphone's position inside the combustion chamber

This technique assumes linear behavior of the acoustic cavity. As such the inherent dynamic characteristics of the combustion chamber are independent of the excitation type and its spectral components. However, the response of an acoustic environment is the same for different excitation.

Radial, axial, as well as coupled frequencies must be measured, to obtain a complete experimental data set, which contains all the acoustic FRF, to be compared with the referred theoretical frequencies. Then, it is important to measure the required acoustic traveling waves, by positioning the microphone in the correct direction, according the transverse or axial measurement axe. As a pressure type microphone was utilized, it was important to place the sensor diaphragm perpendicularly to the direction of the propagating wave.

For each axis, FRF measurements were taken, performing azimuthal swept at each 45º, positioning the microphone in the radial direction at distances 10 mm, 40 mm and 70 mm from the structure wall, and also performing an axial swept, at each 50 mm. Figure 4 shows the position points to obtain the complete set of measurement data.

Observing Fig. 4 one can note that this measurement procedure generates a large amount of experimental data, since transversal data were measured at each 45º, positioned at 10 mm, 40 mm and 70 mm from the structure wall, taking as reference, the geometric center of the combustion chamber. Axial measurements were performed at each 50 mm, up to 450 mm, depending on the chamber length.

It is expected that the propagating waves have a plane wave behavior, as described by Samir 1994. This behavior can be verified when acoustic FRF in all the points of the same plane, perpendicular to the direction of the wave propagation, may not present significant differences. As such, with the test results, this behavior can be verified and the experimental data points can be decreased, consequently, decreasing the amount of data to be analyzed.

3.2 Experimental Results

Resonant frequencies of the combustion chamber were identified, by analyzing some FRF with frequency band from 0 to 5,000 Hz. The acquired FRF were analyzed and an average of the frequencies and magnitudes was done to obtain the set of resonant frequencies of the referred cavity. Figure 5 shows the combustion chamber used on the tests and Fig. 6 display one of the acquired FRF. A more detailed description of the measurement procedures is beyond the scope of this work and was presented by Pirk et al, 2005.

Figure 5: Combustion chamber prototype

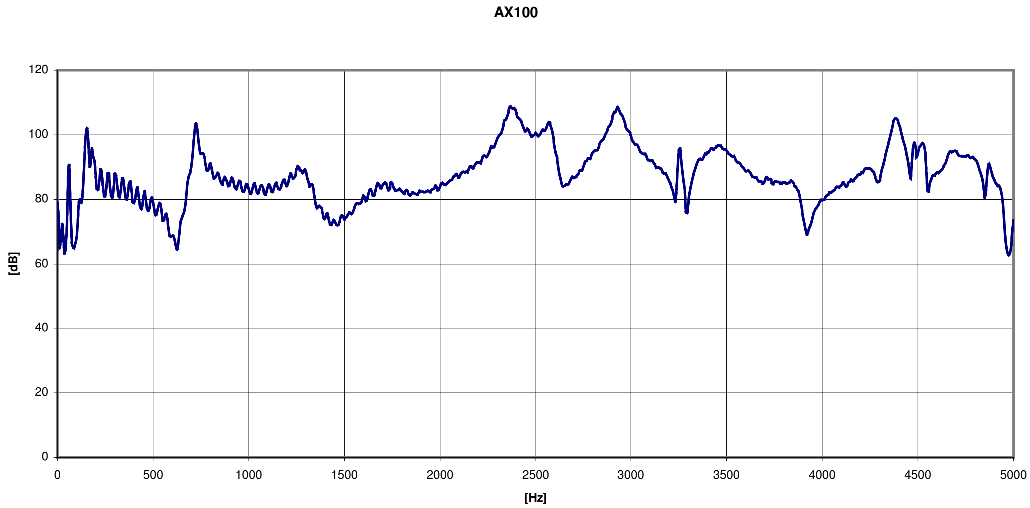


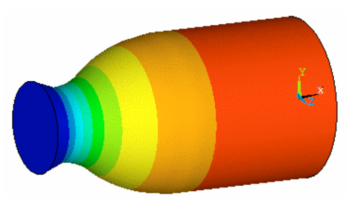
Figure 6 Acquired FRF of the acoustic cavity

Table 1 describes the identified experimental and calculated natural acoustic frequencies, for the chamber shown in Fig.5. These data are compared and an estimate of the error is also described in the referred table.

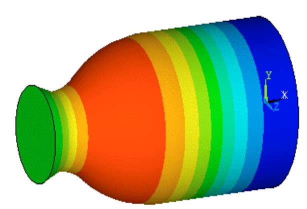
The natural frequencies described on Table 1 were obtained by calculating averages of all measured values, as well as the identified resonances, visualized on FRF curves.

3.3Numerical Results

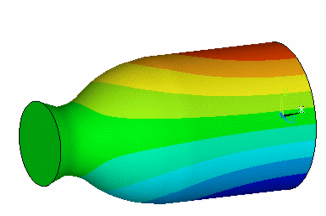
The acoustic modes calculated by the finite element model are shown in the Fig. 7 and Tab. 1 display its frequencies. In Tab.1 (2) indicates the duplicity of a mode. Due to its axisymmetry, the cavity has many double modes.



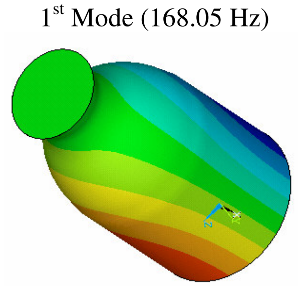
1st Mode (168.05 Hz)



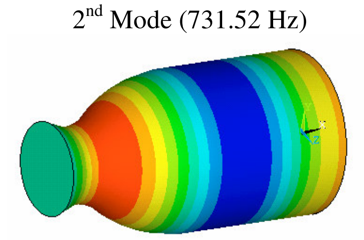
2nd Mode (731.52 Hz)



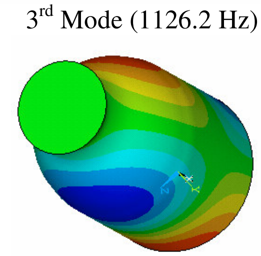
3rd Mode (1126.2 Hz)



4th Mode (1309.6 Hz)



5th Mode (1391.3 Hz)



6th Mode (1813.1 Hz)

Figure 7 - Acoustic mode shapes calculated by ANSYS

Table 1 Natural frequencies of the acoustic cavity

Frequencies (Hz)			
Mode	**FEM**	**Measured**	**Error(%)**
1	168.05		
2	731.52	719,0	1,74
3	1126.2 (2)	1137,5	-0,99
4	1309.6	1272,3	2,93
5	1391.3 (2)		
6	1813.1	1793,2	1,11
7	1842.1 (2)		
8	1845.1 (2)		
9	2048.5 (2)		
10	2304.5		
11	2312.1 (2)		
12	2317.1		
13	2422.5 (2)	2380,0	1,79
14	2512.5		
15	2528.1 (2)	2583,6	-2,15
16	2698.0 (2)		

3.4 Discussion

Some of the modes calculated by the finite element model were not identified experimentally but for those ones which were, the results obtained by the FEM model are in good agreement with the measured natural frequencies, even for the modes beyond the frequency band of 0 to 1049 Hz. In the higher frequency region, the FRF present large quantity of peaks (high modal density) and the frequency separation is a difficult task. By this way some modes could not be well identified experimentally. It is important to mention that the adopted measurement setup (number of points) for an acquisition up to 5,000 Hz introduces a bias error in the frequency domain of 6 Hz approximately, due to the digitizing process. This is another indication that a stochastic treatment is a more consistent approximation of the natural frequencies, since different measurement points and this bias error may be considered.

4. Influence of a Helmhotz ressonator on the acoustic modes of combustion chamber

In this section we analyze the effect caused by the presence of a Helmholtz resonator into another combustion chamber model not physically built yet. Figure 8 show this combustion chamber. Figures 9 and 10 display the meshes used for the without and with resonator cases. The p=0 boundary condition was applied to both models but is shown only in Fig. 9 for a better visualization of the mesh.

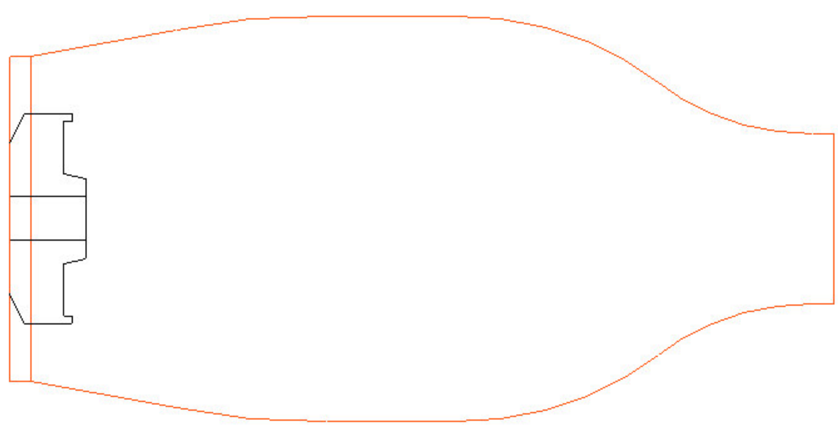


Figure 8 – Combustion chamber with resonator

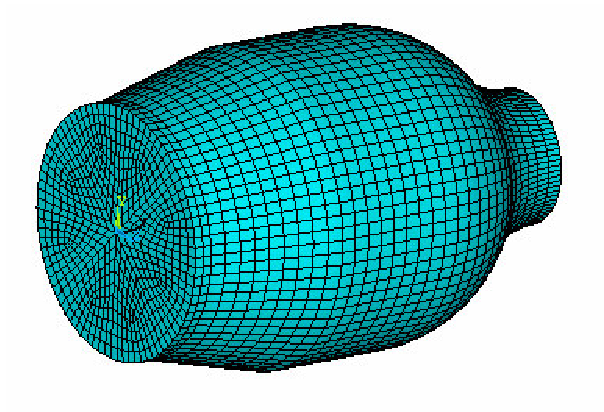


Figure 9 – FEM mesh for the combustion chamber without resonator

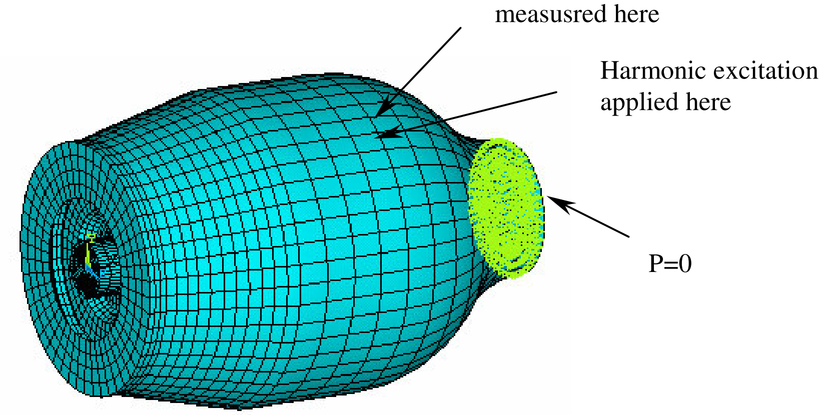


Figure 10 – FEM mesh for the combustion chamber with resonator

For the chamber equipped with resonator, the biggest element in the mesh has a 0.01074 m as its biggest dimension. Assuming 10 elements per wave length, this corresponds to a wave length of 0.1074 m and a maximum frequency of 3247 Hz. For the chamber without resonator these values are 0.004875 m, 0.04875 m and 6974 Hz respectively. The meshes have 13367 (with resonator) and 4820 (without resonator) degrees of freedom. In Tab. 2 the results of the numerical modal analysis performed by ANSYS are displayed (first 13 modes).

Table 2 Natural frequencies with and without resonator

Frequencies (Hz)		
Mode	With resonator	Without resonator
1	738,26	754,91
2	2065,3	3179,9
3	4240,2	4307,4
4	4240,2	4307,4
5	4871,8	5576,8
6	4871,8	5613,4
7	5017,7	5613,4
8	6946,2	6997,1
9	6946,2	6997,1
10	6957,0	7385,3
11	6957,0	7385,3
12	7632,5	7754,4
13	7632,5	8184,9

A response function of the first three modes of Tab. 2 is displayed in Fig.11. A harmonic pressure excitation of 10 Pa with a frequency step of 50 Hz was used to analyze both models (a more refined step was used around the peaks). The positions where the pressure excitation was applied and measured are shown in Fig. 10. One can notice that this resonator not only reduce the natural frequencies of all modes but also reduces the modes amplitude. This is not valid only for the first mode which is (a transversal one) where only the frequency has decreased.

Consequently the energy available to produce combustion instability by coupling the acoustic modes with the combustion process is reduced.

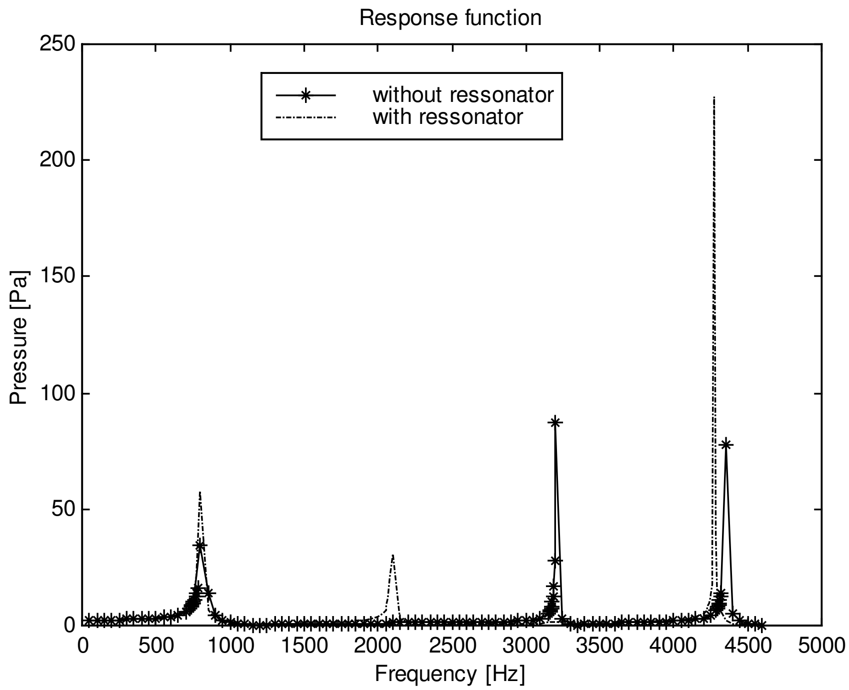


Figure 8 Cavity response functions with and without resonator

5. Conclusions

Dynamic analysis of combustion chambers acoustic cavities was performed by the finite element method. The results are compared to experimental results and good agreement was achieved, although not all modes in the frequency band analyzed seem to be identified experimentally. All the calculations were done considering air at usual temperature and pressure. The effect of placing a Helmholtz resonator into a chamber was also studied numerically.

6. Acknowledgements

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7. References

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