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MODAL IDENTIFICATION OF HYBRID ROCKETS ACOUSTIC CAVITIES: EXPERIMENTAL AND NUMERICAL EVALUATION

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Abstract. *In this paper, numerical and analytical analysis (modal and harmonic analysis) were performed to identify acoustic cavities natural frequencies of combustion chambers. We executed this numerical analysis in commercial platform ANSYS R12. Axisymmetric and 3D models were done. And we observe the effect of combustor chamber's cross-section variation in acoustic's natural frequencies and modal shapes, once the combustion chamber is submitted to a continuous variation in its diameter during combustion. An experimental procedure was devised to compare the numerical and analytical results to experimental data. This procedure permitted the identification of the modes higher than 100 Hz.*

Keywords: *acoustic cavity, modal analyses, FEM, experimental modal identification*

1. INTRODUCTION

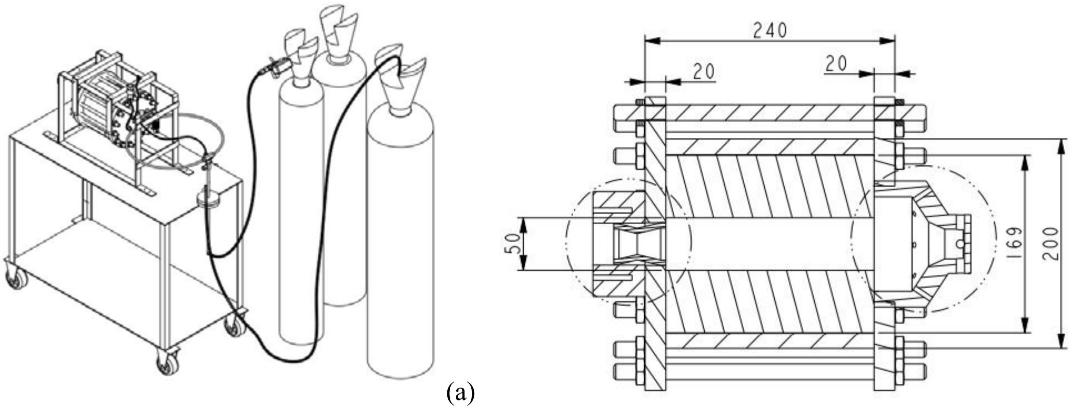
Hybrid rockets propulsion have the potential to be safer, more flexible, and less expensive compared to the others chemical propulsion systems. It can be throttled, stopped, and restarted. The fact of hybrid rockets use a two-phase propellant system is directly connected with the above mentioned advantages but also arises some difficulties like the neutralization of their instabilities. The pressure oscillations observed in hybrid rockets are bounded in amplitude unlike solid motor instabilities. Therefore, hybrid instabilities do not introduce the possibility of catastrophic consequences such as the blow up of the whole motor. However, they generated unpredictable burning rates and also introduce thrust oscillations (Karabeyoglu et al., 2003).

Some authors affirm (Stoia-Djeska and Mingireanu, 2011) that the interaction between acoustic waves and combustions causes self-excited acoustic-type combustion instabilities oscillations. The pressure sensitivity of the combustion process, the coupling motor and oxidizer feed system, the vortex shedding in the aft mixing chambers and others (Marvin, 1990) are the factor responsible by this self-excited oscillations. To verify this assertive, we propose the modal identification of the combustor acoustic cavities.

The numerical analysis (modal and harmonic analysis) is performed using the commercial platform ANSYS R12. Axisymmetric and 3D models are obtained. The effect of combustor chamber's cross-section variation in acoustics' natural frequencies and modal shapes are observed. An experimental procedure was devised to compare the numerical and analytical results to experimental data. This procedure permitted the identification of the modes higher than 100 Hz.

2. HYBRID ROCKETS PROPULSION: ATUAL CONTEXT AND LABORATORY-SCALE TEST-RING

The experimental setup (Figure 1 a) composed by three cylinders: one containing the oxidizer (GOx – Gaseous Oxygen) and the other two were part of the ignition system (composed by pressurized air and GLP). An electric pneumatic valve controls GPL flux while a solenoid valve controls the air flux. At ignition time both valves are open and when me mixture get into motor an electric scintilla starts a primitive flame, in this moment the main flux of gaseous oxygen is freed by a high pressure electro pneumatic valve and the ignition systems are ended. Figure 1b shows a schema of the engine.



(a) (b)

Figure 1. Motor stand test (a) and Motor Assembly (b).

The data acquisition systems for fire tests was compost by an ADS500 data acquisition system work together an ADS100 A/D – D/A converter (acquisition frequency 4 kHz each channel) by lynx technology. This system was receiving data from pressure transducers – one in the combustion chamber (by Sitron/0-50bar) and two in the oxidizer lines (by Wika/0-100bar) and thermocouples by Thermomax (4 – two in the nozzle and two in the oxidizer line) and a load cell by Primax (0/100kg). Their results are analyzed with the software AdDados 7.02.

3. NUMERICAL AND ANALYTICAL ANALYSIS

Numerical and analytical results were obtained for the characterization of the acoustic properties of the motor cavity. The geometry was obtained from a preliminary CAD drawing from the motor cavity. This drawing was simplified for both the numerical and analytical solutions.

The numerical solution was obtained using a finite element acoustic model using the P-U method with commercial software ANSYS R12. The fluid element used was a three-dimensional fluid element (FLUID30) and the boundary conditions are as shown in Figure 2.

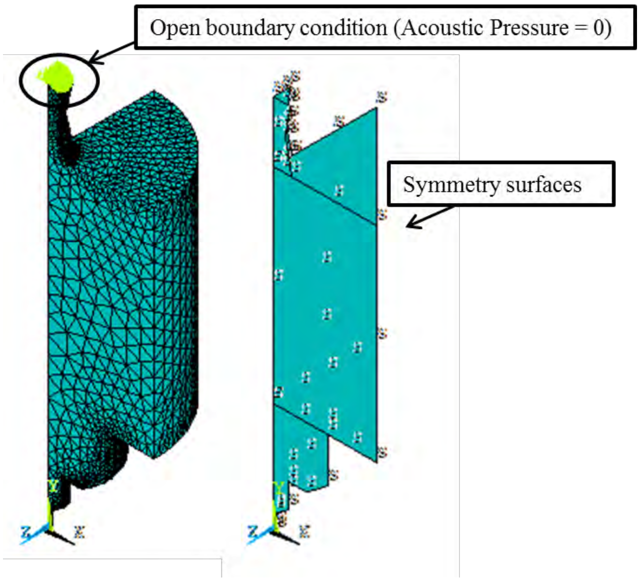


Figure 2. Mesh and boundary conditions from the numerical model

The analytical result considers the cavity an open Helmholtz resonator and uses a transfer function method to obtain the first resonance frequency. The dimensions of the motor cavity will change over time, once the burning of the grain gradually enlarges its interior, a subroutine was created to obtain various results for the maximum and minimum values of its diameter. The geometry was simplified so that a transfer function method could be used to determine the Helmholtz resonator frequency of the cavity. According to Kinsler et al. (1999), the shape of the cavity of volume V is not important in determining its Helmholtz resonator natural frequency, given that the dimensions of the cavity are much smaller than the acoustic wavelength. This is fortunate, as we may obtain this frequency using a simple equation, given by many authors (Kinsler et al., 1999; Costa, 2003). The results shown in Figure 3 suggest that this first mode in the numerical model corresponds to a Helmholtz mode. This can be verified analyzing the first mode shapes for the various diameters. It can be observed that the cavity will act as a Helmholtz resonator up from the main cavity diameter of 110 mm.

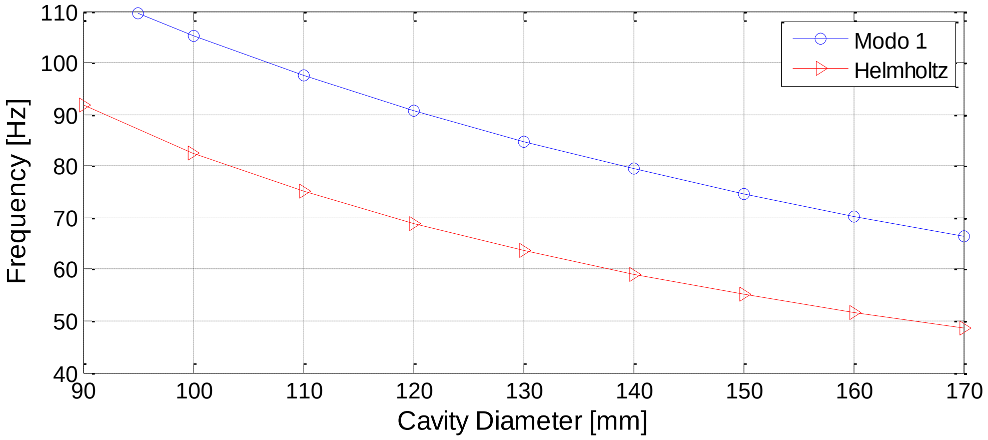
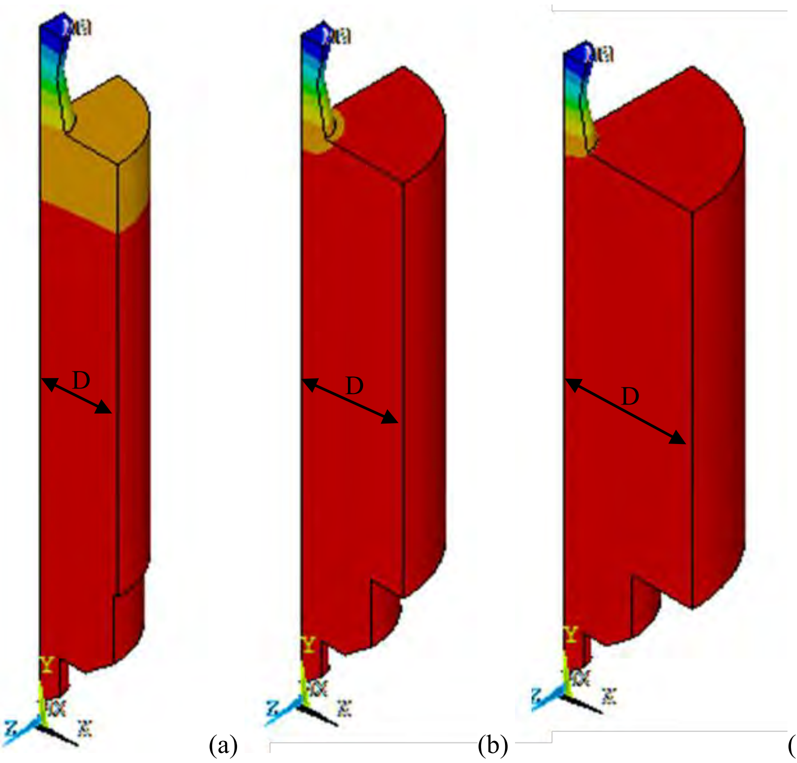


Figure 3. Comparison between numerical results (FEM) and Helmholtz frequency for the motor assembly cavity

In Figure 4, we can clearly see that cavities (d) and (e) are acting as Helmholtz resonators. Cavity (c), which corresponds to a cavity diameter of 95 mm, can be regarded as a Helmholtz cavity, but the rate of the neck and cavity diameter is not as accentuated as in (d) and (e), which have cavity diameters of respectively 130 and 170 mm.



(a) (b) (c)

Figure 4 . Numerical results for the first mode shapes of the motor assembly cavity for three different cavity diameters. (a) D=95 mm, (b) D=130 mm, (c) D=170 mm

The study of the frequency spectrum of the cavity acoustic mode shapes for different diameters shows us that this Helmholtz frequency will be accentuated by a cavity diameter decrease, even if this phenomenon is only observed for the higher frequency mode shapes, as shown in Figure 5 and Figure 6.

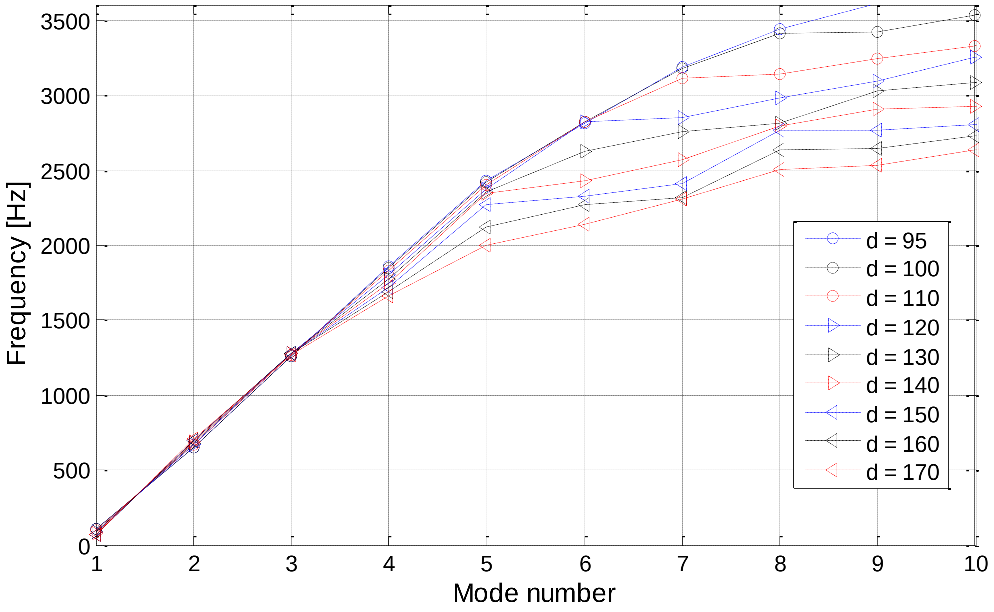


Figure 5. Acoustic mode frequency distribution for motor assembly cavities of different diameters

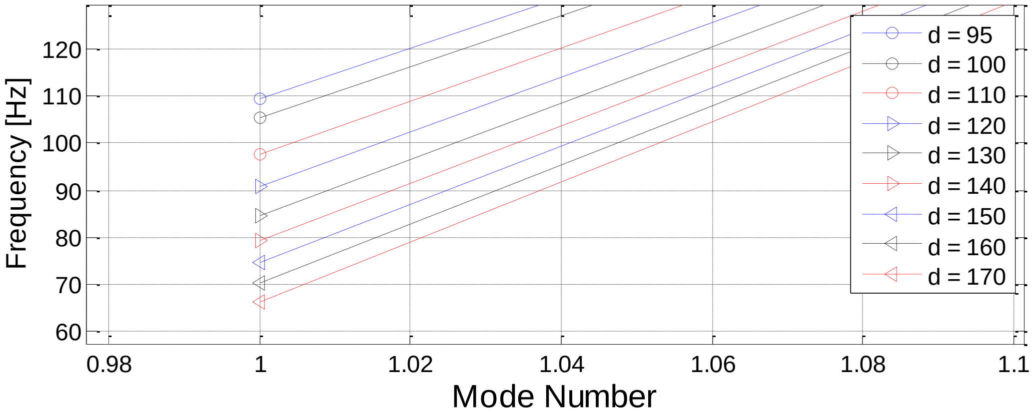


Figure 6. First mode frequency for motor assembly cavities of different diameters

The only acoustic modes that are in the frequency band associated with the structure are the first for every cavity diameter. From the set of these modes, the cavity with the lower frequency is the 170 mm cavity diameter. For this diameter the cavity acts as a Helmholtz resonator.

Table 1. Modal shapes of 3D axisymmetric model

Frequency	**1**	**2**	**3**	**4**	**5**
Numeric 3D - ϕ = 95mm	109.50	648.13	1257.2	1858.6	2427.8
Numeric 3D - ϕ = 130mm	84.720	682.58	1280.1	1779.9	2361.2
Numeric 3D - ϕ = 170mm	66.423	703.69	1271.2	1665.2	1996.9

The five first mode shapes for the cavity corresponding to a cavity diameter of 170 mm-Figure 7.

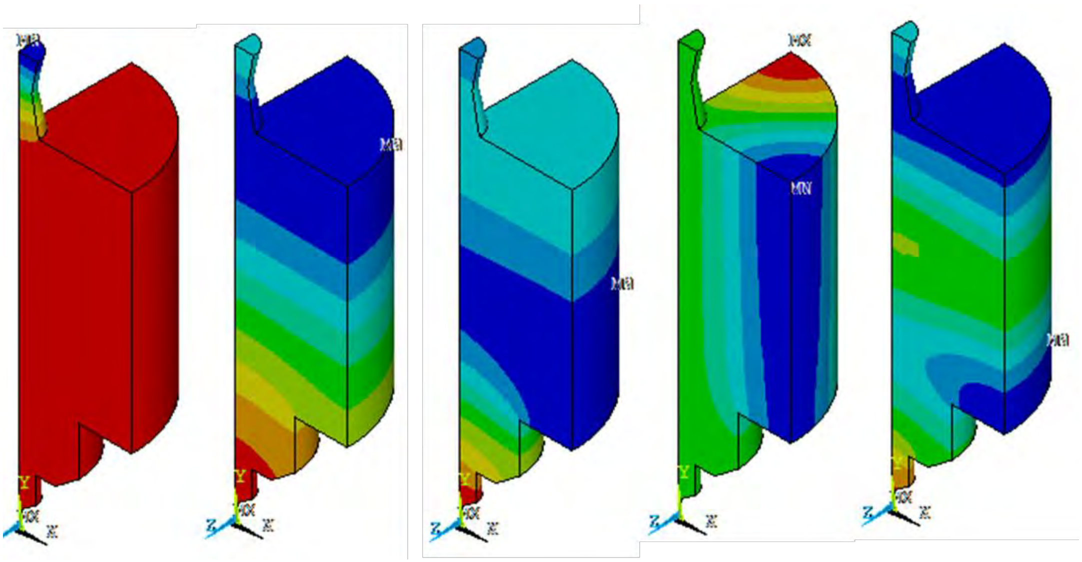


Figure 7. Five first mode shapes for the acoustic cavity

4. DESCRIPTION OF EXPERIMENTAL APPARATUS

To evaluate the natural frequency of the motor assembly cavity, a procedure was created based on acoustic modal analysis with calibrated source (Rossetto, 2001; Melo et al., 2012; Melo, 2013). This experimental procedure use a speaker connects to a flexible duct measured by one microphone (reference microphone). This experimental apparatus, shown in Figure 8, allows us to know the acoustic excitation that’s getting inside the cavity. With another microphone (measure microphone) locate at the cavity of interest, it’s possible to determine experimental frequency response functions (FRF) and identify modal characteristics of acoustic cavity.

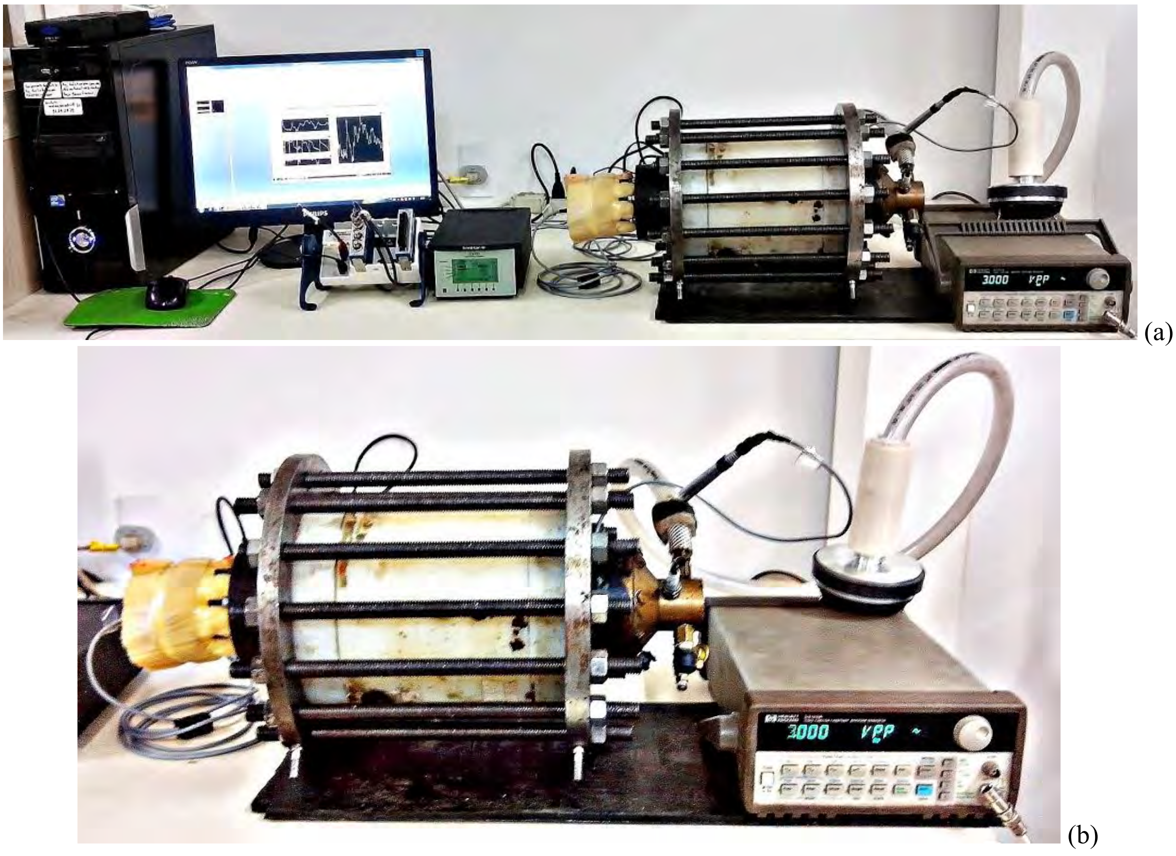


Figure 8. Scheme of experimental procedures (a) and detail of motor assembly cavity with acoustic source/wave generator (b)

The experimental essays were carried out with a Selenium D220TI 8 Ω speaker with a frequency broadband of 20-20k Hz, a wave generator HP 33120A, microphones Bürel & Kjaer 194537 connected to a Bürel & Kjaer NEXUS amplifier. The data acquisition device is a National Instruments CompactDAQ NI9174 and NI9234 interfaced by LabView. The frequency response functions (FRF) of the acoustic dynamic signal are obtained by LabView software.

The source signal to excite the acoustic cavity is a logarithmic sweep sine with a broadband of 100-3000Hz during a period of 1.5 seconds and 3 Vpp of magnification. The frequency step is about 0.5 Hz. The amplification of the microphone signal was 1V/Pa for the measurement microphone and 100mV/Pa for the reference microphone.

To determine the maximum frequency the consideration of plane waves was used, once the use a calibrated source considers that the source is a monopole (Rossetto, 2001), the high impedance, defined by Ewins (Ewins, 2001), is yet another result of the use of the calibrated source (Rossetto, 2001). The coherence value was used to define the minimum frequency perceived. When the coherence is above 0.98 is defined the minimum frequency, which was around 180 Hz.

5. EXPERIMENTAL RESULTS AND COMPARATION WITH NUMERICAL/ANALYTICAL ANALYSIS

The results were obtained in Brasília, Brazil, about 1000 m above sea level, ambient temperature of 22-24 ºC and humidity around 62%. The essays were done in the morning of March 28 2013. Only one essay was carried out in a single day, consisting of 50 repetitions. The final result is the mean value of this 50 repetitions.

Figure 9 shows the experimental FRF corresponding to the motor assembly acoustic cavity. This figure presents signal magnitude in p^2/Hz (dB) and signal phase in degrees (°). In this graph, the first four natural frequencies obtained by numerical analysis are compared to the experimental results. These four natural frequencies were presented as a range corresponding to several diameters of principal cavity.

We observe a reasonably agreement with the first two natural frequencies seen in Figure 9.

The **first frequency** corresponds to a Helmholtz resonator, as described in section 3. This Helmholtz frequency was not clearly identified, because our calibrated source cut-off frequency is around 100Hz while the Helmholtz resonator frequency is on 50-100Hz interval. But we observe a disturbance in phase which indicates a natural frequency. Then we need to apply supplementary analysis using low-frequency techniques (impact hammer analysis) to surely identify this mode.

The **second frequency** corresponds to a first frequency of cavity. This cavity frequency is more clearly identified. The **third frequency** was not matched correctly. More extensive studies are needed to identify this natural frequency influenced by viscous loss effect perhaps. And the **forth frequency** corresponds to a transversal mode, Figure 7. Then it was not possible to identify in Figure 9 due to the position of measure microphone.

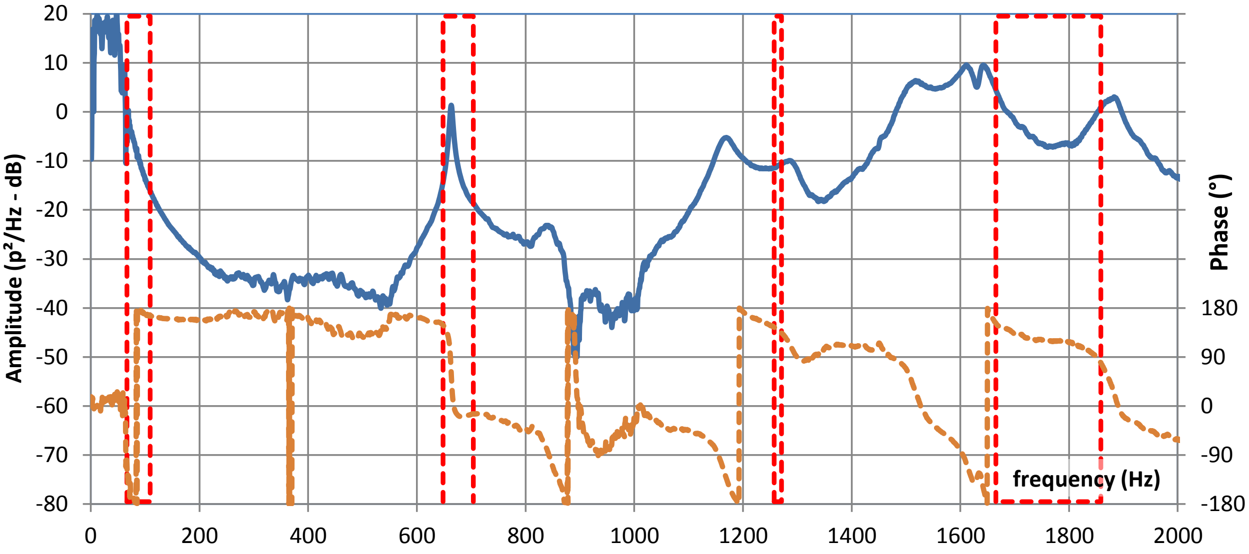


Figure 9. Experimental FRF (amplitude p^2/Hz(dB) and phase (°)) of acoustic motor assembly compare to first four numerical natural frequency range. This frequency range corresponds to physical diameter of principal cavity (ϕ_{min} = 95mm to ϕ_{max} = 95mm)

Figure 10 shows the experimental FRF results for a motor acoustic cavity with combustion test (Karabeyoglu et al., 2005). In this experimental test, it can be observed Helmholtz resonator describe as the chamber's bulk mode. And the first acoustic frequency of the cavity may be described as a chamber 1-L acoustic mode. Both results correspond to isothermal essay without flow presented at this paper. This results is encouraging to realize posterior essays with flow.

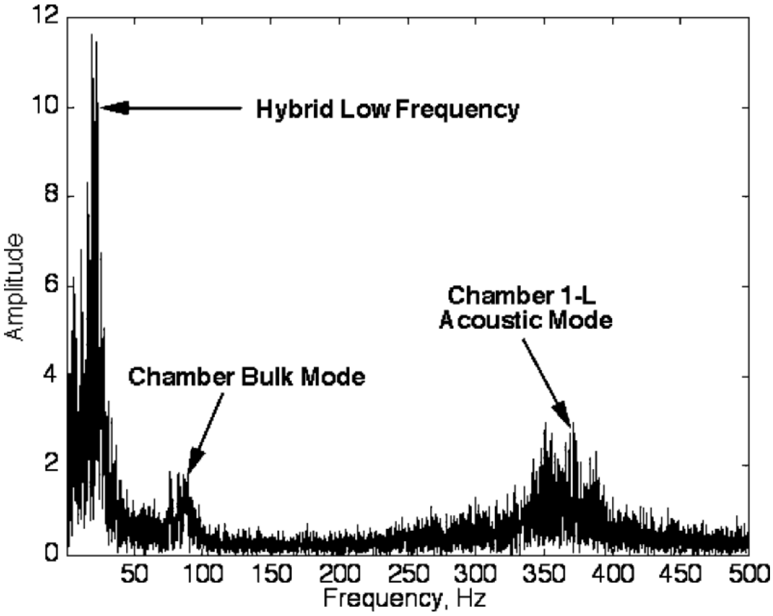


Figure 10. Fourier transform of chamber pressure for the paraffin-based motor test (Karabeyoglu et al., 2005)

6. CONCLUSION

In this work, we identify numerically and experimentally the acoustic natural frequencies of a hybrid motor assembly cavity. FE numerical modeling was conducted using commercial platform ANSYS R12 to describe a close-open motor cavity by modal and harmonic analysis. Experimental analysis identifies natural frequencies of motor assembly cavity using a procedure of acoustic modal analysis by calibrated source.

The FE analysis was performed with a variation of the internal diameter of the main cavity to study the natural frequency range. It can be observed that this influence is minor on the first four natural frequencies. Due to internal diameter variation, the first natural frequency observes a variation inferior to 10Hz. This first natural frequency works as a Helmholtz resonator that could be compared to analytical simplified formulas.

In case of experimental analysis, we could identify the first four acoustic modes. The first, second and fourth frequencies are recognized as a Helmholtz resonator, a first acoustic frequency of cavity, and a transversal frequency, respectively. Comparing to experimental results, numerical simulation describes reasonably the phenomena. And the literature results with mean flow show similarities by report to present experimental results and numerical solution.

The perspective to next works is describing the acoustic behavior of hybrid motor cavities with mean flow isothermal.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE

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