# CHARACTERIZATION OF A SINGLE CYLINDER RESEARCH ENGINE RELATED TO KNOCK

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***Abstract.*** *The occurrence of the knock phenomenon follows the development of the ignition spark internal combustion engine from its invention and, even today, constitutes a major limitation in achieving both high performance and in the preservation of its integrity. Thus, a more detailed understanding of this phenomenon is desirable, necessary and configures itself as a major challenge for researchers. In the case of single cylinder research engines, this need is even greater for two reasons: its high cost and expensive delays in the research activities arising from the possible shutdown due to problems related to the occurrence of knock.*
*This paper describes the initial steps of the methodology used to characterize the knock phenomenon in a single cylinder research engine used for research focused on the application area of power generation. Are addressed primarily the calculations used, from the consideration of a simplified geometry for the combustion chamber, for determining the frequency content with the occurrence of knock and the use of finite element method for the identification of acoustic modes present in the combustion chamber. This characterization covered so far the different conditions of operation of the engine (air dilution), different fuel injection systems (direct injection and indirect injection) as well as some types of flow structure (low, medium and high swirl) considering CNG as fuel. The main results obtained are presented beyond the next steps to be followed in order to complete the characterization of the engine related to knock.*

***Keywords:*** *Knock, Internal Combustion Engine, Single Cylinder Research Engine, Finite Element Method*

## 1. INTRODUCTION

The use of alternative fuels in Brazil (Compressed Natural Gas and ethanol, among others) has been gaining in recent years, an increasing importance. Whether for use in the automotive industry is for application in power generation, such fuels have been very promising. In this sense, it becomes necessary to develop the know-how built capable of researching and developing new technologies applied to internal combustion engines seeking high performance and low fuel consumption, compatible to the best Diesel cycle engines currently available. Thus, a more detailed understanding of knock phenomenon in the engine is desirable and necessary because this phenomenon is one of the major limitations to achieving high performance in an internal combustion engine.

The importance of understanding so profound aspects related to knock phenomenon is the fact that it can, depending on its intensity, rapidly compromise the physical integrity of an internal combustion engine. In particular, considering its occurrence in a single cylinder research engine, such importance is even greater because besides the cost of an engine of this type is very high the losses in terms of their downtime can seriously compromise the planning of research activities based on it.

It is currently developing a methodology for characterizing a single cylinder research engine related to knock phenomenon which covers analytical calculations, computer simulation and experimental tests with various types of sensors. Moreover, it was tested different flow structures and various configurations of fuel injection systems. Tests were also carried out with different fuels: ethanol and Compressed Natural Gas. This work covers two initial stages of the above methodology and presents the results obtained so far and their comparative analysis. Reviews are also provided for future steps to be carried out in order to complete the proposed methodology.

## 2. HISTORICAL

As Heywood (1988), the combustion process is an important part of the operating cycle of an internal combustion engine and should happen in a small fraction of the full cycle so that the energy conversion process is efficient.

According to the same author, specifically in spark ignition internal combustion engine, the combustion process is an extremely complicated combination of phenomena. It involves an electrical arc discharge, chemical oxidation of fuel, heat loss in a complex geometry and the influence of the turbulence of the flow structure.

In the case of combustion with the occurrence of knock this scenario becomes even more complex because in addition to all the factors mentioned above are involved in other phenomena of high complexity, namely: the occurrence of high levels of pressure and temperature inside the cylinder, generation of pressure waves inside the combustion chamber, the cylinder walls reflection of pressure waves generated due to the occurrence of knock creating a profile of complex pressure waves in the combustion chamber and the transmission of vibrations originated inside the cylinder to the engine block.

Historically, the cavity resonance from the knock in gasoline engines were, according Hickling *et al.* (1983), first studied by Draper (1938) who conducted an analysis of resonances and made measurements of the lowest modes in a single cylinder research engine. He used also the analytical solution of wave equation for a closed cylinder with both ends flat for the calculation of frequencies associated with the various modes of vibration induced by knock.

As Grandin and Denbratt (2002), combustion with the occurrence of knock follows the development of the spark ignition internal combustion engine since its invention.

According to Hettinger *et al.* (2010), the knock has been the focus of attention by many researchers for over a century. However, only recently has an understanding of the complex mechanisms that lead to knock is beginning to be unraveled.

## 3. DEFINITION AND KNOCK TEORY

Knock, according to Heywood (1988), is the name given to the noise that is transmitted through the structure of the engine when essentially spontaneous ignition of the unburned portion of the gas - a mixture of fuel, air and waste gas ahead of the flame propagation process - happens.

According Puzinauskas (1992), there are basically three theories concerning the knock phenomenon that seek to determine its origin, namely:

- auto-ignition theory: unburned mixture placed the flame front coming from the spark plug (called main) reaches a high temperature to the point that undergoes auto-ignition in one or more points;
- detonation theory: the normal flame front undergoes a transition from subsonic deflagration to a supersonic detonation coupled to a shock wave;
- rapid-entrainment theory: the normal flame front is accelerated to high, but still subsonic, causing rapid rates of increase of pressure.

In Grandin and Denbratt (2002), it is confirmed that, currently, it is generally accepted that the knock in spark ignition engines is caused by auto-ignition in the unburned mixture.

## 4. KNOCK CHARACTERISTICS

The knock phenomenon covers various aspects of which the most important to be known are: frequency content, factors that influence its occurrence, ways to avoid that and its effects.

### 4.1. Frequency content

From the acoustic point of view, determining the frequency content present in the pressure wave inside the combustion chamber during the occurrence of the knock phenomenon is one of the most important information to be obtained because of that depends on the efficiency of knock detection and analysis methods.

According to Brunt *et al.* (1998), good understanding of the acoustic modes is very useful in measurement and analysis of knock, particularly in relation to the filtering effects, and also in defining the best location for the pressure transducers to be used.

As cited in Carstens-Behrens *at al.* (2002), the resonances of the combustion chambers of combustion engines of spark ignition are slightly excited during normal combustion but strongly excited when the knock occurs.

According to Eng (2002), can be excited, basically, three different types of acoustic modes, namely:

- Circumferential: where nodes make longitudinal planes passing through the diameter of the cylinder;
- Radial: where nodes make plans extending from cycles concentric with the cylinder axis;
- Axial: where nodes make plans perpendicular to the longitudinal axis of the cylinder (rarely excited).

According to Scholl *et al.* (1997), the frequencies on the axial modes depend on the angle of the crankshaft while those on the radial and circumferential modes are independent of it.

Figure 1 illustrates the form of some types of acoustic modes: circumferential, radial and combined.

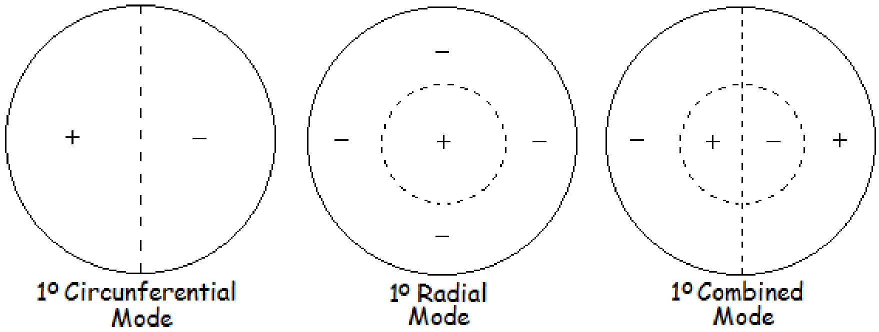



Figure 1 – Acoustic modes

Regarding the energy involved in the knock phenomenon, according to Shi (2005), simulation computer results indicate that the first two acoustic modes have most of the acoustic energy and thus the pressure on knock has a maximum value at those frequencies.

According to Eng (2002), the lowest resonance frequency in a cylinder is that corresponding to the first circumferential mode which contains most of the energy present in the pressure wave. As a result, this is the frequency at which most researchers have concentrated when quantifying the intensity of knock.

### 4.2. Factors that influence the knock

As cited in Schelling and Geisselbrecht (2000), the knock phenomenon must be evaluated from the point of view statistic given the highly irregular nature of the operation cycles of an internal combustion engine. In this sense, are cited in the literature, the main factors influencing the occurrence and severity of knock, namely: design features of the engine, fuel composition, engine operating conditions, location of the spark plug, the flow structure of the mixture in the combustion chamber (swirl or tumble), the mixture formation process **-** Direct Injection (DI) or Fuel Injection in the Portic (PFI) **-** and pressure and temperature of unburned gas.

### 4.3. Ways to prevent knock

Similarly to the factors that influence the occurrence of knock, in the literature are listed the main alternatives to avoid or suppress the occurrence of the same, namely: improving the octane number of fuel, reducing the ignition advance angle, enrichment the mixture, optimization of the geometry of the combustion chamber, use of cooled EGR, the use of engine with variable compression ratio and use of fuel mixed with high octane components such as ethanol, methanol and others.

Recently, Yunlong *et al.* (2010) proposed the concept of stratified stoichiometric mixture (SSM) as an alternative to avoid the occurrence of knock in spark ignition engines with direct fuel injection (DISI) for operating conditions at high loads. Such an alternative is to create, at the time of ignition by a second fuel injection, a region rich in the mixture around the spark plug and a lean mixture in the other areas of the combustion chamber including the waste gas while maintaining the stoichiometric ratio air / fuel mixture total.

The rich region tends to speed the burning of the flame while the residual gas suppresses the tendency to autoignition and such combined effects reduce the intensity of knock.

### 4.4. Effects of knock phenomena

As cited in Kaelblein *et al.* (1990), the effects of knock in ignition-spark internal combustion engines can be classified depending on their occurrence and intensity in three different types:

- Benefit effect: related to the increase in value of IMEP (Indicated Mean Effective Pressure) which is due to increased efficiency of energy conversion. This increase is caused by the acceleration of the spread of flame front which, in turn, implies a rapid exchange of heat, particularly outside of the waste gas near the TDC (Top Dead Center);
- Harmful effects: reduction of engine power output due to the uncontrolled exchange of heat, high heat transfer and friction and simultaneously to increased levels of gaseous emissions.
- Destructive effects: damage to the physical integrity of engines such as mergers and / or breakage of piston rings, head gasket failure, erosion of the upper piston, holes and / or merger of the piston, the spark plug melting and deformation of valves.

## 5. METHODOLOGY TO CHARACTERIZATION OF THE KNOCK PHENOMENON

In this work, characterization of the knock phenomenon can be understood as the identification of the frequency spectrum present within the combustion chamber of the single cylinder research engine due to the occurrence of the knock phenomenon. In this sense, basically, there are three different alternatives: analytical calculation, computer simulation using FEM and experimental determination.

The complete methodology to be used for the characterization of the SCRE related to the knock can be viewed by Fig. 2.

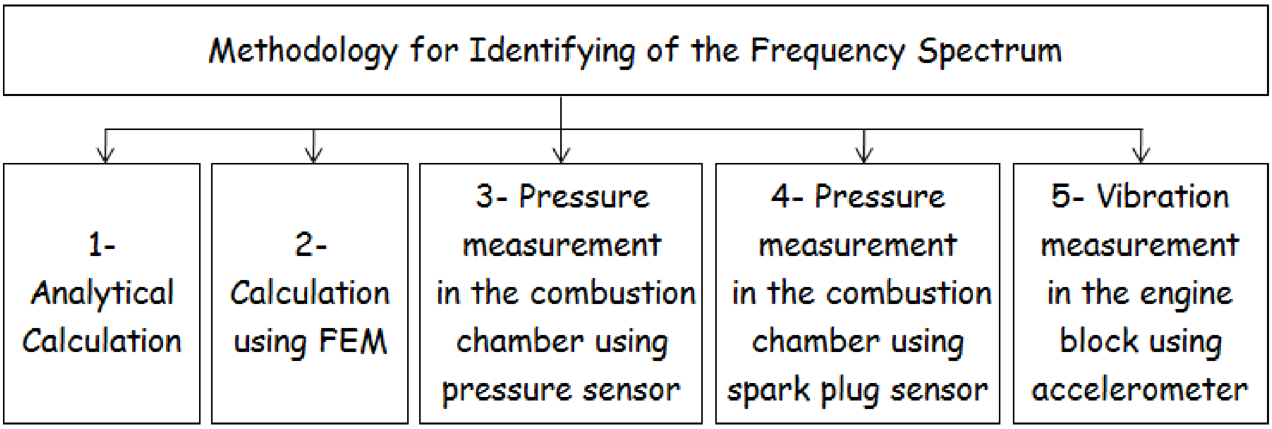



Figure 2. Methodology for characterization of the single cylinder research engine

### 5.1. Analytical calculation

As cited in Draper (1938), the prediction of the types of pressure waves present in the combustion chamber when the occurrence of knock involves obtaining a solution of the wave equation for certain boundary conditions. This procedure involves the following assumptions:

- the amplitude of the pressure wave caused by knock is small compared to the average pressure inside the cylinder;
- the velocity, normal to the cylinder walls, of the the particles of the mixture in the combustion chamber is zero.

Mathematically, as quoted by Hickling *et al.* (1983) has the wave equation:

$$\nabla^2 p + \frac{W^2}{V^2} p = 0 \tag{1}$$

where:

$p$ : pressure inside the combustion chamber;
$V$ : sound velocity, calculated from equation 2:
$W = 2\pi f$ : angular frequency;

$$V = \sqrt{\gamma \cdot 287.1848 \cdot T} \tag{2}$$

where:

$\gamma$ : ratio of the specific heat at constant pressure and specific heat at constant volume;
T : maximum temperature of burned mass.

Draper (1938) proposed the use of graphics to facilitate the determination of resonance frequencies present in a combustion chamber with simplified geometry: parallel bases cylinder.

In this work, that alternative was used to provide a first idea of the range of frequencies present in the combustion chamber.

**5.2. Computer simulation**

Finite Element Modelling (FEM) is another important modeling alternative. It is essentially applicable to engines where the real geometry of the combustion chambers is rather complex, Schmillen and Rechs (1991). Besides allowing the determination of the frequency content present in the combustion chamber it has the additional advantage of being able to cope with the visualization the acoustic modes, therefore being most useful for their interpretation and analysis of results.

In this work, that alternative was used to indicate and to understand better the behavior of acoustic modes present in the combustion chamber depending on the crankshaft angle. The goal is to identify the frequencies of the main acoustic modes (determined from the actual geometry of the engine: in this case, geometries of the piston and cylinder head) for comparison with analytical calculations.

This simulation will also serve for future comparison with experimental results to be obtained through the use of pressure sensor and spark plug sensor inside the combustion chamber.

**5.3. Experimental determination**

One of the most useful experimental procedures is to measure the signal of the pressure inside the combustion chamber (either using a spark plug sensor **-** SPS **-** or a pressure sensor **-** PS) or vibration signal (accelerometer) on the engine block and, subsequently, processing these signals. In this case, the type of sensor used and its positioning inside the combustion chamber or on the engine block, are crucial in obtaining the signals and analyzing their results. This alternative for determining the frequency content is still under development and analysis and will not be considered in this paper.

**6. RESULTS**

For reference, Tab. 1 shows the main technical characteristics of the single cylinder research engine (SCRE) used for testing.

Tabela 1. Technical characteristics of single cylinder research engine

| | |
|---|---|
| Supplier | Ricardo |
| Model | Proteus II |
| Nominal Displacement | 2.056 liters |
| Bore / Stroke | 128 / 160 mm |
| Connecting rod length | 256 mm |
| Compression ratio | 13:1 |
| Operating speed | 1800 rpm |
| Valve train | 4V DOHC |
| Air intake system | Normally aspirated |
| Fuel | Ethanol and CNG |
| Flow structure | Low Swirl / Medium Swirl / High Swirl |
| Injection system | Fuel Injection in the Portic (PFI)<br>and Direct Injection (DI) |

The actual values of flow structure were based on a scale defined by supplier and theirs values varied from 0 up to 3.00: low swirl (0.12), medium swirl (1.54) and high swirl (3.00).

Still considering the characterization of the Single Cylinder Research Engine was considered the following settings listed in Tab. 2.

Table 2. Evaluated configurations

| Injection System | Fuel | Flow Structure | Lambda |
|---|---|---|---|
| PFI | CNG | Low Swirl | 1.0 |
| | | | 1.3 |
| | | | 1.5 |
| Direct Injection Air Assisted | CNG | Low Swirl | 1.3 |
| | | High Swirl | |
| | | Medium Swirl | |

This paper covers the steps "1- Analytical Calculation" and "2- Calculation using FEM" listed in Fig. 2. The later stages are under development and testing and are not considered here.

The comparative evaluations performed to characterize the single cylinder research engine were:

- the influence of the lambda value: configuration PFI CNG;
- the influence of the flow structure: configuration Direct Injection Air Assisted CNG.

### 6.1. Analytical calculation: results

Initially an analytical calculation was performed for the configuration Direct Injection Air Assisted CNG and value of lambda equal to 1.3 considering the combustion chamber as a cylinder of parallel bases.

The necessary conditions for the analytical calculation were obtained from the simulation using the software GT-Power which, in turn, used the single cylinder engine experiments. This procedure was used in order to obtain values that could be compared more accurately to those obtained through computer simulation. Basically, it was used the following data: ratio of specific heat at constant pressure to specific pressure at constant volume, (depending on the crankshaft angle) and maximum temperature of the mass burning (also depending on the crankshaft angle).

This calculation was based on the table cited in Draper (1938) and used the following equations:

$$f = \frac{V}{\lambda} \tag{3}$$

where:

$\lambda$ : wavelength - iquals ( 3.4 * 0. 128) for the first circumferential mode, as cited in Draper (1938);
$V$ : from Equation (2).

Figure 3 illustrates the comparison between the results of this calculation and FEM simulation for the mode 2 (first circumferential mode).

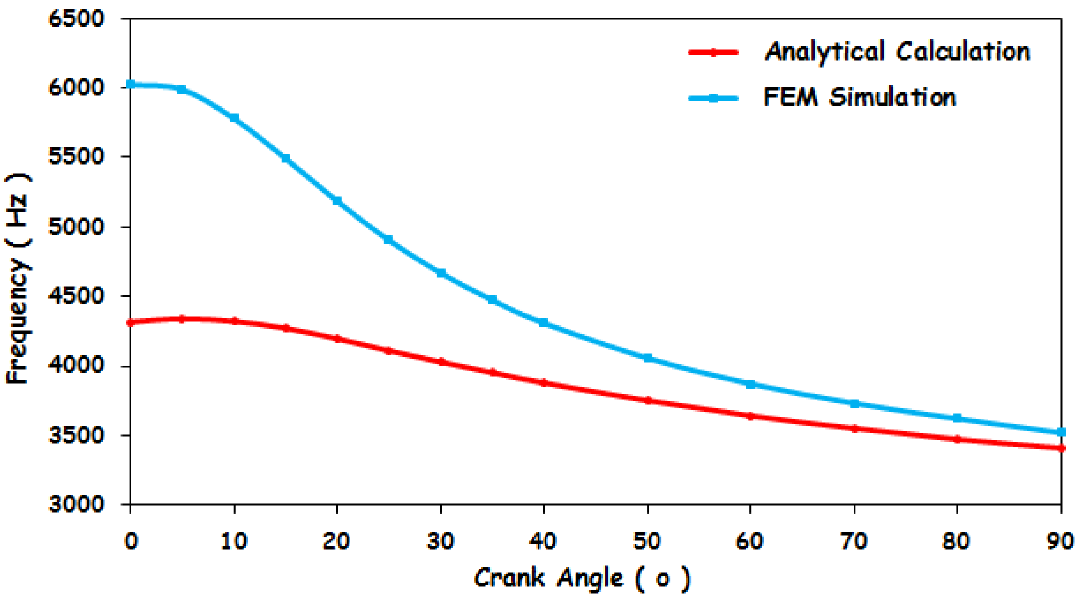



Figure 3. Comparison of analytical calculation and FEM simulation results

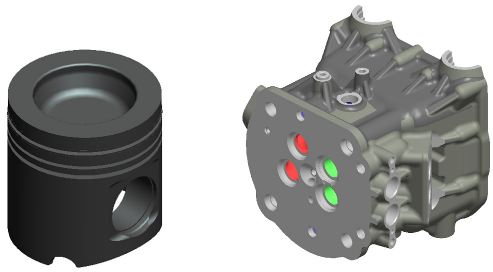
As can be seen, there is a large discrepancy between the results for the crank angle near TDC. This difference tends to be smaller as the piston moves to the Bottom Dead Center (BDC): difference of 28.4 % for CA of 0° and 3.1 % for AC at 90°. This can be easily explained by the geometry of the piston. The presence of the bowl violates the assumption that the combustion chamber can be considered as a cylinder of parallel bases especially when the piston is at TDC. But when the piston is at the BDC that consideration is not totally absurd, and thus the results are presented closer to the simulation. It is expected that the results are closer to crankshaft angles around 180° (BDC).

The same trend was also observed for other values of lambda. Thus, the analytical calculation can be considered unfeasible, for this geometry of the piston, in determining the values of resonance frequency of the combustion chamber when the occurrence of knock.

**6.2. Computer simulation using FEM**

This simulation used the actual geometry of the piston and the cylinder head to determine the acoustic modes present in the combustion chamber, according to the crankshaft angle. The values of the crankshaft angle had been chosen in order to sweep the period where the detonation occurs most commonly, and also allow an analysis of the progress of the acoustic modes as a function of that angle. Figure 4 illustrates these geometries.

Piston



Cylinder head

Figure 4. Engine actual geometry

The finite element mesh used to model the combustion chamber in the acoustic modes simulation was created using the software Hypermesh v10.0 and their characteristics are shown in Tab. 3. It was considered the minimum number of seven points in each wavelength to ensure reliable results.

Table 3. Characteristics of the finite element mesh

| Item | Characteristic |
|---|---|
| Element type | Tetrahedral ($1^a$ order) |
| Number of elements | 58235 ( $0^o$ CA)<br>200772 ($90^o$ CA) |
| Maximum size of the elements (mm) | 3.0 |
| Maximum frequency (kHz) | 27.3 ( $0^o$ CA)<br>37.2 ($90^o$ CA) |

The model mentioned above was prepared in order greater convenience in the simulation of acoustic modes for different angles of the crankshaft. Thus, this model was divided into two separate volumes, namely:

- Fixed volume: composed of the volume created between the cylinder head and piston with the same positioned at top dead center (TDC). This volume was kept fixed for all angles of the crankshaft and included simulated volume referring to the bowl;
- Variable volume: volume created as a function of piston displacement in accordance with its positioning .

The same procedure was used in Carstens-Behrens et al (2002) in their research of knock.

The necessary conditions for the simulation, using the software ABAQUS v 6.10, were obtained from the simulation using the software GT-Power which, in turn, used the single cylinder engine experiments. This procedure was used in order to obtain values that could be compared more accurately to those obtained experimentally using pressure transducers (spark plug sensor and pressure sensor). These stages of the methodology are not considered in this paper.

Basically, for the determination of the acoustic modes were required the following data: geometry of the cylinder head, piston engine geometry, modulus of bulk (depending on the crankshaft angle) and density of the burned mass (according to the crankshaft angle) obtained from the simulation with the GT-Power.

Acoustic modes were simulated for the following crankshaft angles: 0, 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80 and $90^o$.

To get a preview of the kinds of acoustics modes found in the combustion chamber, Figure 5 illustrates the top ten acoustic modes (not considered mode 1: rigid body) to a crankshaft angle of $10^o$ considering the condition of lambda equal to 1.0.

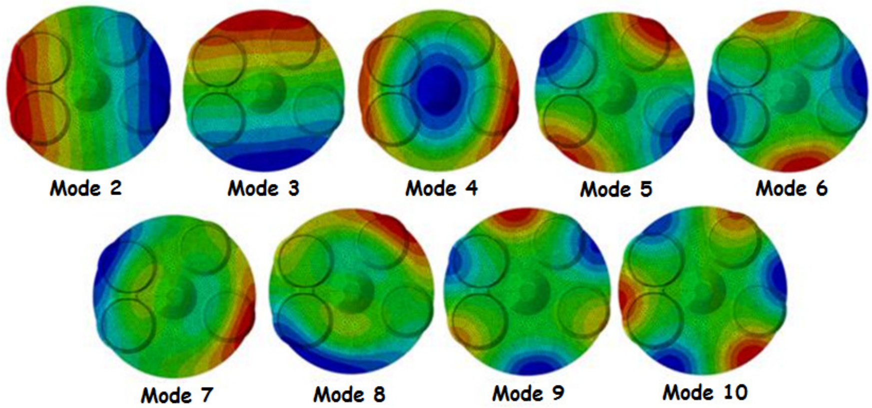



Figure 5. Acoustic modes

Can be identified the following acoustic modes:
- Modes 2 and 3: first circumferential mode. Frequency modulated , values differ in frequency depending on the geometry of the combustion chamber. Are lagged one another by an angle of $90^o$;
- Mode 4: the first radial mode;
- Modes 5 and 6: second circumferential mode. Frequency modulated, values differ in frequency depending on the geometry of the combustion chamber. Are lagged one another by an angle of $45^o$;
- Modes 7 and 8 combined modes;
- Modes 9 and 10: third circumferential mode. Frequency modulated, values differ in frequency depending on the geometry of the combustion chamber.

The first simulation was performed to verify the influence of dilution of this mixture inside the combustion chamber. Figure 6 illustrates the influence of lambda value in the results obtained for the frequency range in the setting PFI CNG.

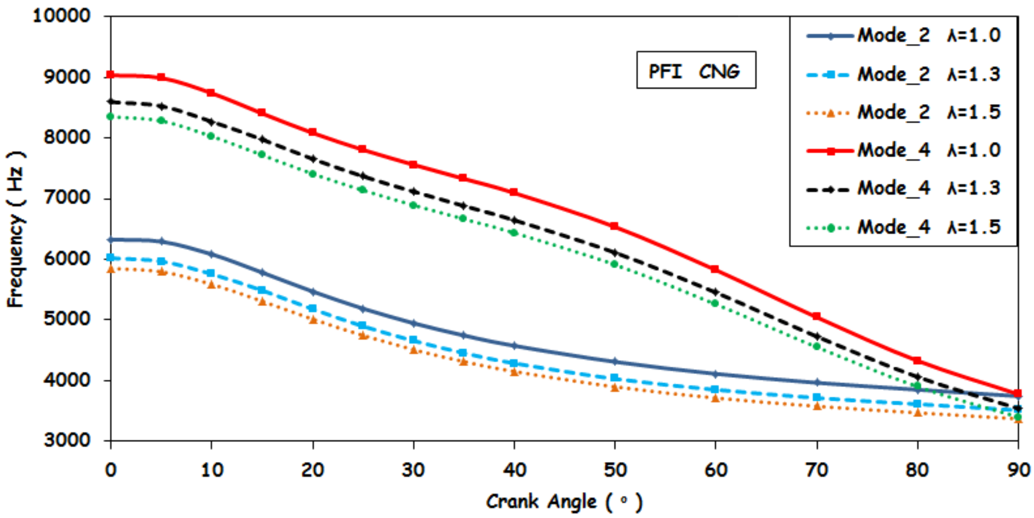



Figure 6. Comparison of lambda values: configuration PFI CNG

Specifically, for the acoustic mode 2, there was a significant difference in frequency values simulated according to the values of lambda: the biggest difference between the extreme values of lambda was 496.1 Hz (for a crankshaft angle of around 5º after TDC). As for the acoustic mode 4, the largest difference found was 710.9 Hz (for crankshaft angle of around $10^o$ after TDC). The same behavior as a function of lambda was found for other acoustic modes.

Thus, the use of different dilution values significantly affects the values of resonance frequencies present in the combustion chamber: the richer the mixture the greater the values of frequencies. This is explained by the higher values of temperature, sound velocity and hence the frequencies for the case of richer mixtures.

Figure 7 illustrates the influence of different flow structures in the simulated results for the frequency setting Direct Injection CNG.

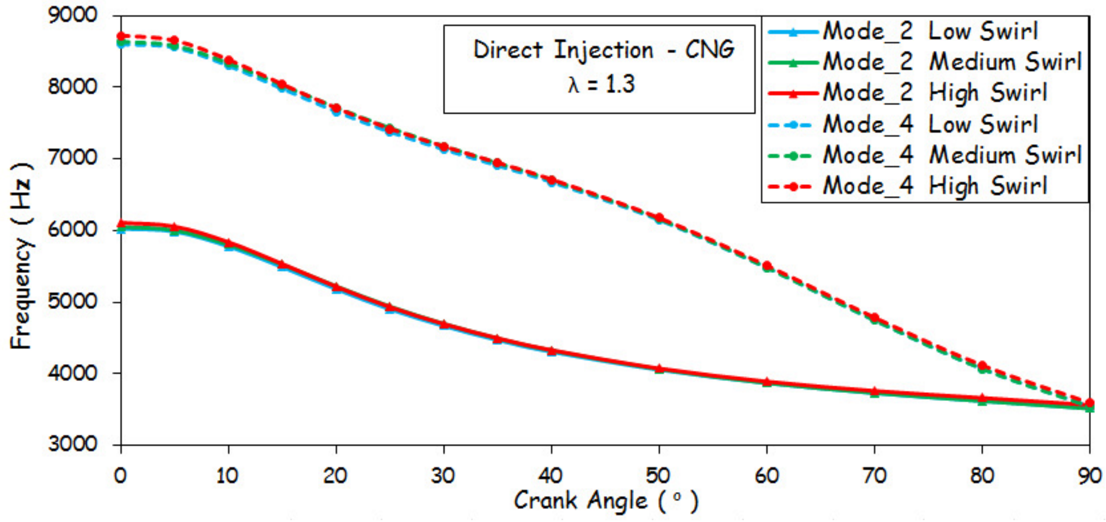



Figure 7. Comparison of flux structure: configuration Direct Injection Air Assisted CNG

For different flow structures tested, there were no significant differences in the values of frequencies for both mode 2 (circumferential) and for mode 4 (radial).

## 7. CONCLUSIONS

From the results is possible to conclude the following points:

**-** The mathematical calculation, initially regarded as a preliminary estimate of the frequency content, was not accurate when compared to the results obtained from computer simulation (actual geometry). This can be explained by the geometry of the combustion chamber of this engine (presence of the bowl). Thus, it consider the use of mathematical calculation as a unfeasible alternative to motor into account;

**-** The use of computer simulation has proved very useful in order to view the various types of acoustic modes present during the occurrence of knock and will be particularly useful in comparing with the results of experimental measurements (step to be performed later);

**-** Simulated results showed a significant difference depending on the lambda value. This is interesting for the fact that research with the single cylinder engine can cover an extensive range of lambda values being dependent on the objective of the research (eg, optimization of consumption);

**-** Simulated results showed that the type of flow structure does not influence the frequency values obtained for the Direct Injection Air Assisted CNG.

## 8. FUTURE STEPS

The next steps to be followed to finalize the methodology for the characterization of the single cylinder engine is to perform the comparative analysis of results obtained from two pressure sensors located at various points of the combustion chamber and an accelerometer mounted on the engine block. Such analysis will also cover a comparison with results of computer simulation of the acoustic modes.

## 9. ACKNOWLEDGEMENTS

The authors would like to thank VSE – Vale Soluções em Energia the opportunity to use its single cylinder research engine and the dynamometer for the realization of the experiments. In addition, we thank especially to Engineer Henrique Moritz for the creation of mathematical models using the software GT-Power and Engineer Felipe Rodrigo Cardoso for carrying out the acoustic modes computer simulation using Abaqus software.

## 10. REFERENCES

Brunt, M. F. J., Pond, C. R. and Biundo, J., 1998. "Gasoline Engine Knock Analysis using Cylinder Pressure Data". *900po21AE World Congress Detroit, Michigan, Paper 980896.*

Carstens-Behrens, S., Urlaub, M., Böhme, Johann F., Förster, J. and Raichle, F., 2002. "FEM Approximation of Internal Combustion Chambers for Knock Investigations". 2002. *SAE World Congress Detroit, Michigan March 4-7,* Paper 2002-01-0237.

Draper, C. S., 1938. "Pressure Waves Accompanying Detonation in the Internal Combustion Engine". *Journal of the Aeronautical Sciences,* Volume 5, Number 6.

Eng, J. A., 2002. "Characterization of Pressure Waves in HCCI Combustion". 2002. *SAE World Congress Detroit, Michigan* March 04-07, Paper 2002-01-2859.

Grandin, B. and Denbratt, I., 2002. "The Effect of Knock on Heat Transfer in SI Engines". *SAE 2002 World Congress Detroit, Michigan, Paper 2002-01-0238.*

Hettinger, A., Kulzer, A. and Spicher, U.,2010. "Higher specific load – increasing knock risk evaluation of measures for knock reduction using multiple pressure indication". *9th International Symposium on Combustion Diagnostics, Kurhaus Baden-Baden*.

Heywood, J.B. *Internal Combustion Engine Fundamentals*, New York, NY: McGraw-Hill,1988. 930 p.

Hickling, R., Feldmaier, D. A., Chen, F. H. K. and Morel, J. S., 1983. "Cavity resonances in engine combustion chambers and some applications". *J. Acoustical Society America* 73 (4), April.

Kaelblein, T., Jeong, Y. 1. and Rhee, K. T., 1990. "Knock Effects on Spark-ignition Engine Emission and Performance", *International Congress and Exposition, Detroit, Michigan* February 26- March 2. Paper 900712.

Puzinauskas, P. V., 1992. "Examination of Methods used to Characterize Engine Knock". *International Congress & Exposition Detroit, Michigan, Paper 920808.*

Schelling, H. and Geisselbrecht, M., 2000. "Measurement of Various Influencing Factors on Piston Load During Knocking Combustion". *Mahle Technical Information*.

Schmillen, K. P. and Rechs, M., 1991. "Different Methods of Knock Detection and Knock Control", *International Congress and Exposition, Detroit, Michigan* February 25-March 1. Paper 910858.

Scholl, D., Barash, T., Russ, S. and Stockhausen, W., 1997. "Spectrogram Analysis of Accelerometer-Based Spark Knock detection Waveforms". *International Congress and Exposition, Detroit, Michigan* February 24-27 Paper 972020.

Shi, Y., "Prediction of Knock Sensor Locations with Background Noise", 2005. *SAE World Congress Detroit, Michigan* April 11-14, Paper 2005-01-2554.

Yunlong, B., Zhi, W. and Jianxin, W., 2010. "Knocking Suppression using Stratified Stoichiometric Mixture in a DISI Engine". *SAE 2010 World Congress Detroit, Michigan, April,* Paper 2010-01-0597.

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