# Investigation of the Knock in an Engine BASF Using Vibration Analysis

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## ABSTRACT

This article presents an analysis of the knock in a BASF internal combustion engine through vibration monitoring using accelerometers. Knock, a phenomenon that compromises engine efficiency and durability, occurs when combustion happens before the ignition point, while the piston is still compressing the mixture. This generates a counterforce to the piston's upward movement, potentially causing damage to internal combustion chamber components. Knock was investigated through acquisition and processing of vibrational signals from the engine block. Ethanol Hydrated was added to gasoline to verify its influence on this phenomenon.

Signal analysis techniques, including Fourier Transform, Envelope, and Band-Pass Filter, were applied to identify characteristic patterns of abnormal combustion. Results indicated a strong correlation between vibration levels and knock occurrence, evidencing the effectiveness of accelerometers for early detection. This study reinforces the importance of vibration analysis as a non-intrusive tool for monitoring and controlling internal combustion engine (ICE) performance.

The experiment determined the knock point at a compression ratio of 8.6:1 for the base fuel, Brazilian regular gasoline containing 28% anhydrous ethanol in its standard composition. From this value, tests with additional ethanol Hydrated in the base fuel samples proved the effectiveness of ethanol as an anti-knock agent.

## 1. INTRODUCTION

The development of internal combustion engines (ICE) is directly linked to the advancement of industry on the global stage, aiming to accelerate human procedures in performing tasks and to ease labor demands by reducing the reliance on human and animal strength, and minimizing physical wear. Internal combustion engines were invented around 1860 and, since then, engineers and researchers have worked to make them more powerful and efficient

Knock is an abnormal combustion phenomenon that occurs in spark-ignition engines, characterized by the spontaneous ignition of the air-fuel mixture under pressure in the combustion chamber before the normal flame front propagation. This event can cause mechanical damage to the engine and reduce its thermal efficiency (HEYWOOD, 1988). A fuel's resistance to knock is commonly expressed by its octane number (ON), with higher ON values indicating greater resistance to knocking.

The addition of ethanol to gasoline has been widely investigated as a strategy to increase ON and reduce pollutant emissions, while also representing a renewable and environmentally friendly alternative (ZHU et al., 2016). Ethanol has a high-octane rating and significant evaporative cooling capacity, which contributes to reducing knock tendency, especially in engines operating with high compression ratios, such as the BASF engine, commonly used for fuel characterization tests. The present work aims to evaluate the effect of ethanol addition to gasoline on knock resistance using a BASF engine.

Studies in the literature also highlight the importance of vibration analysis in ICE research. In the study by Tormos et al. (2002), the use of an accelerometer installed on the block of an internal combustion engine enabled the acquisition of time-domain signals over several thermodynamic cycles, allowing for analysis that identified injection system faults, compression loss, starter anomalies, and mechanical failures such as cylinder or piston clearances, bearing and shaft issues, and especially problems in the cylinders. Another study, conducted by Bares et al. (2018), demonstrated that vibration signal analysis can correlate with knock events in spark-ignition engines, using accelerometers to capture specific vibrational signatures.

According to principles described in technical literature on ICEs, such as in Pulkrabek (2004), the combustion frequency of an engine is associated with its speed, number of pistons, and operational cycle type. In single-cylinder four-stroke engines, combustion occurs every two crankshaft revolutions, whereas in two-stroke engines, it happens every revolution. This relationship is essential for determining the combustion frequency, which can be calculated using Equation 1:

$$f = \frac{RPM \cdot n}{60 \cdot T}$$

Where f is the combustion frequency (Hz), RPM is the engine's revolutions per minute, indicating crankshaft rotation speed; n is the number of pistons, determining how many combustion events occur per cycle; and T is the number of crankshaft revolutions to complete a combustion cycle, with T = 2 for four-stroke engines and T = 1 for two-stroke engines.

## 2.MATERIALS

The tests using the BASF engine were conducted in the Engine Laboratory of the Department of Thermal and Fluid Sciences (DCTEF) at the Federal University of São João del-Rei (UFSJ).

Figure 1 provides an overview of the assembled BASF engine setup, showing the starter motor, cooling system, and carburetion system.

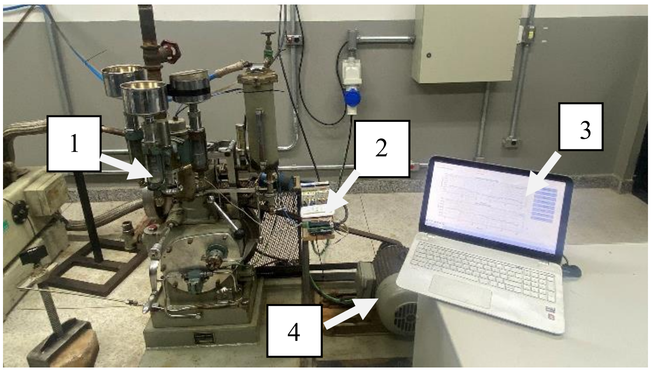


**Figure 1. BASF Engine (1) | Data acquisition system (2) | Computer with signal processing software (3) | Electric starter motor of the BASF (4).**

For the development of the experimental test, the following instruments were used: the BASF engine, a data acquisition system for monitoring temperature and rotation, type K thermocouples, SKF Microlog GX 75 vibration data collector equipped with SKF CMS 2200 accelerometer, and SKF @ptitude software for interpreting signals in the time domain and spectra.

### 2.1 BASF ENGINE

The BASF is a single-cylinder engine capable of varying its compression ratio between 4:1 and 12:1. This variation is achieved by moving the cylinder head vertically via a crank and worm gear mechanism. No other adjustment is needed to change the compression ratio.

### 2.2 DATA ACQUISITION SYSTEM

To develop the data acquisition system for engine speed and air-fuel mixture temperature, an Arduino Uno system was used. This is an open-source electronic prototyping platform, allowing the installation and programming of a wide range of sensors, actuators, and software for data acquisition and transmission. The system transmits results in real-time to its integrated display, as shown in Figure 2.

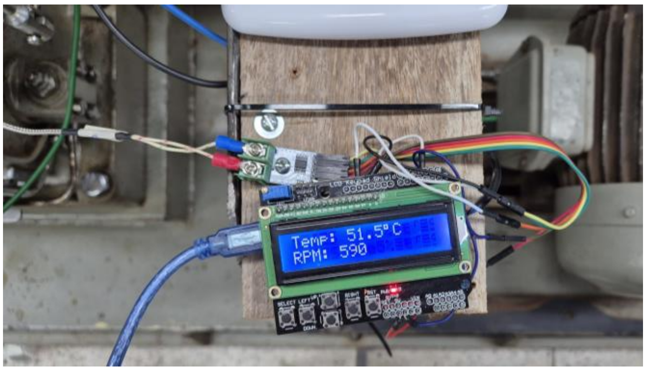


**Figure 2. Data acquisition system.**

Once the data acquisition system was defined, a program was developed to measure speed and temperature using C++ language with an inductive sensor for measuring the rotation and a type K thermocouple for measuring the air-fuel mixture temperature. To record and analyze the data, a graphical interface was developed in Python for displaying measurements from the sensors connected to the Arduino Uno (Figure 3).

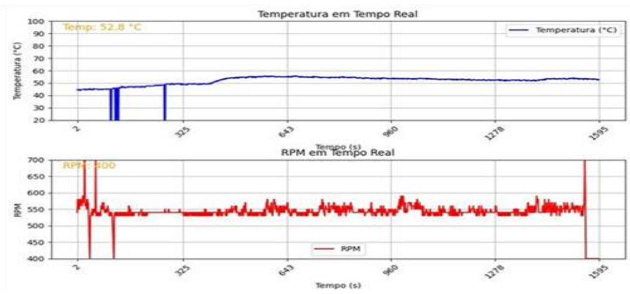


**Figure 3. Graphical Interface | Temperature and Speed.**

The data is transmitted through the serial port COM5 from the Arduino, processed by the software, and displayed in real-time on the computer screen, allowing monitoring of the necessary parameters for the experiment. In addition to real-time monitoring, the program enabled data storage for future analysis and record keeping.

A proximity inductive sensor NPN - LJ12A3-4-Z/BX was installed on a bracket positioned near a toothed wheel on the engine crankshaft, capturing the engine's speed in real-time based on electromagnetic induction principles.

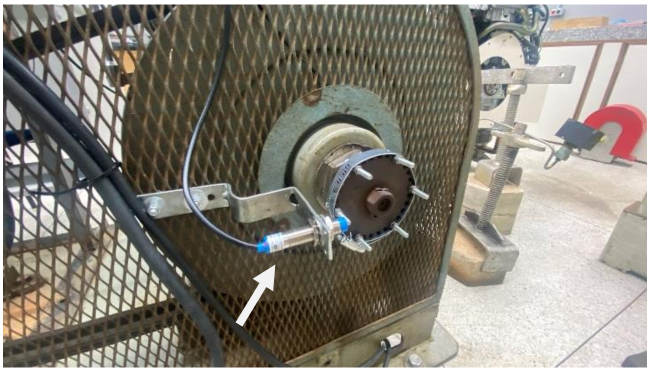

**Figure 4. Rotation sensor coupled to the engine shaft.**

To measure the air-fuel mixture temperature, a type K thermocouple sensor (Figure 5) was installed in the location formerly occupied by a mercury globe thermometer.

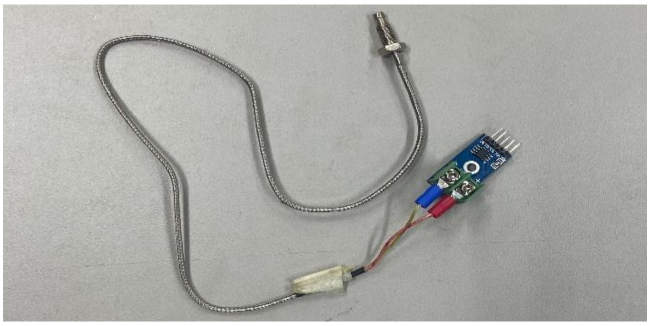

**Figure 5. Type K thermocouple temperature sensor and MAX6675 module.**

This sensor operates in the 0°C to 800°C range and transmits this information as a digital signal to the Arduino via a MAX6675 reading module. This setup maintains the mixture temperature at approximately 52 ± 1.0°C, as proposed by the Research Octane Number (RON) method (LOUER, W., 2008).

**2.3 MICROLOG GX 75 – PARAMETERIZATION**

To ensure accurate capture of vibration signals, three configurations were defined, covering different frequency ranges and analysis techniques, including standard vibration measurements and envelope analysis. The settings used are as follows:

- Nyquist frequency: 2500 Hz | Detection: g – Peak | Acquisition time: 2.56 seconds | FFT lines: 6400 | Averages: 2 | Window: Hanning.
- Nyquist frequency: 10000 Hz | Detection: g – Peak | Acquisition time: 2.56 seconds | FFT lines: 25600 | Averages: 2 | Window: Hanning.
- Envelope | Nyquist frequency: 100 Hz | Detection: gE – Peak | Acquisition time: 2 seconds | FFT lines: 200 | Averages: 2 | Filter: Band 50 - 1000 Hz | Window: Hanning.

**2.4 FUELS**

The tests used fuels (gasoline and ethanol hydrated) available in the Brazilian market, purchased from fuel stations in the municipality of São João del-Rei, Minas Gerais.

This gasoline contains 27 ± 1% ethanol anhydrous in its composition, as specified by Brazilian Law No. 14.993/2024. To confirm this information, washing tests were performed, which revealed a 28% ethanol anhydrous content in the mixture, as shown in Figure 6.

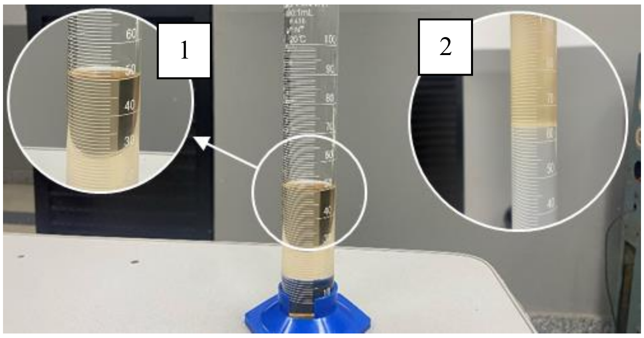


**Figure 6. Ethanol percentage measurement in a gasoline sample, where (1) represents gasoline before washing, and (2) shows gasoline mixed with water, indicating 28% ethanol in the mixture.**

**3. METHODOLOGY**

The RON (Research Octane Number) method was adopted as the base testing methodology to define basic parameters such as the minimum engine temperature for test initiation, minimum air-fuel mixture temperature, spark pulse advance angle, and average engine speed (LOUER, W., 2008).

To determine the sensitivity of ethanol's anti-knock power in gasoline, the following steps were followed: engine warm-up, identification of the compression ratio at which the base fuel (gasoline) begins to knock, preparation of fuel samples with varying ethanol percentages, and testing of those samples to observe knock behavior with varying ethanol hydrated content.

Vibration monitoring was conducted on the test engine by positioning the accelerometer vertically. According to Arnone et al. (2010), the vertical plane shows higher vibration levels compared to horizontal and axial planes due to the greater influence of dynamic forces from the combustion process.

The vibrational signals were processed and analyzed within frequency ranges previously identified as relevant based on the vibration spectra. The frequency bands of interest considered were: 0 to 2500 Hz, 2500 to 3500 Hz, 5500 to 6500 Hz, and 7000 to 8000 Hz. Signal comparison was based on two main metrics: (i) peaks observed in the Frequency Spectrum (FFT) within the bands of interest and in the Envelope of the Time Signal around the combustion frequency; (ii) peaks in the Time Signal and its Envelope over time, associated with the period corresponding to the combustion frequency.

## 3.1 ENGINE WARM-UP

To ensure consistent results unaffected by engine temperature variations, it was established that prior to beginning data collection and testing, the engine must be warmed up for 10 minutes during which the cooling system temperature reaches 100 ± 1°C, considered appropriate for the RON method (LOUER, W., 2008).

Furthermore, according to the RON method (LOUER, W., 2008), the air-fuel mixture temperature should be maintained at approximately 52 ± 1.0°C. This is controlled through a manually activated electric resistance heating system (Figure 7).

**Figure 7. Heating system with electric resistance.**

## 3.2 DETERMINATION OF THE COMPRESSION RATIO AT WHICH THE BASE FUEL KNOCKS

To determine the engine compression ratio at which the base fuel begins to knock, the compression ratio varied in 0.2:1 increments according to the engine's compression scale (Figure 8). Each compression ratio was held for 3 minutes until the engine stabilized, after which vibration data collection began to check for knock occurrence.

Once the compression ratio associated with knocking was identified, the test cycle was repeated to confirm measurement accuracy and eliminate potential errors. A minimum of three fuel samples were analyzed.


**Figure 8. Compression ratio indicator wheel.**

## 3.3 PREPARATION OF FUEL SAMPLES WITH VARYING ETHANOL HYDRATED CONTENT

Burettes were used to prepare fuel samples by varying the ethanol hydrated content in the mixture as needed to determine sensitivity.

As baseline information, gasoline was mixed with ethanol in proportions defined in Table 1:

| Sample | Ethanol hydrated added to gasoline in ml | Brazilian regular gasoline containing 28% anhydrous ethanol in ml |
|---|---|---|
| 1 - Base | - | 100 |
| 2 | 16 | 100 |
| 3 | 17 | 100 |
| 4 | 18 | 100 |
| 5 | 19 | 100 |
| 6 | 20 | 100 |
| 7 | 21 | 100 |

**Table 1. Ethanol percentage in the mixture for various samples.**

## 3.4 TESTING OF THE FUEL SAMPLES WITH VARYING ETHANOL HYDRATED PERCENTAGES

After the preparation of the fuel samples, tests were conducted to verify the presence of knock. These tests followed the same methodology starting with the engine warm-up, but in this time with the compression ratio fixed at the value previously determined as the knock threshold for the base fuel.

## 4. EXPERIMENTATION

The experiment began by fueling the BASF engine with the acquired gasoline, which contains 28% anhydrous ethanol (Sample 1 - Base). The compression ratio was initially set to 7.2:1. The electric motor was then activated to start the BASF combustion engine. From this point on, the engine warm-up procedure began, using the data acquisition system to monitor the engine's coolant temperature and rotation.

When the coolant temperature and engine speed reached 100 ± 1°C and approximately 550 rpm, respectively, and the air-fuel mixture temperature was within the 52 ± 1.0°C range, vibration data collection was initiated. These vibration data were compared to baseline measurements taken with the BASF engine operating without fuel and without electrical power. It was observed that no knock occurred during this baseline measurement.

The same procedure was repeated for compression ratios of 7.6:1, 7.8:1, 8.0:1, 8.2:1, 8.4:1, and 8.6:1, following the previously described methodology for determining the compression ratio at which knock occurs. During the measurement at a compression ratio of 8.6:1, a significant change in vibration level was observed, indicating the occurrence of fuel knock. This change was accompanied by an increase in the intensity of vibration peaks and the appearance of new frequencies in the spectrum.

## 5. ANALYSING AND DISCUSSING THE RESULTS.

The first stage of the investigation involved obtaining the vibrational signature of the BASF engine operating at a compression ratio of 7.6:1 under knock-free conditions, using gasoline as fuel. This analysis was carried out to establish a reference pattern for the engine's vibrational behavior under ideal operating conditions. The collected data served as a basis for comparison with operating conditions in which knock occurred, allowing for the identification of vibrational patterns associated with this phenomenon.

Knock characterization was carried out based on two main indicators: (i) a significant increase in amplitudes within the frequency bands of interest, particularly between 0 and 2500 Hz, as well as peaks near the combustion frequency in the Envelope Spectrum; and (ii) the presence of peaks in the Time Domain Signal, with a period corresponding to the combustion frequency, estimated at approximately 4.5 Hz for the BASF engine at the analyzed operating speed (according to Equation 1, in the 550-600 RPM range).

The envelope technique was used to complement the vibration analysis, with a focus on detecting amplitude variations around the combustion frequency (4.5 Hz). This technique involves extracting the envelope of the time-domain signal, enabling the identification of repetitive patterns associated with combustion events.

Figures 9 to 12, obtained using the SKF @ptitude software, show the vibrational behavior of the BASF engine operating at a compression ratio of 7.6:1, under conditions of normal and stable combustion, without the occurrence of knock. These results are essential for comparison with operating conditions in which knock is present, allowing for the identification of changes in vibrational patterns associated with this phenomenon.

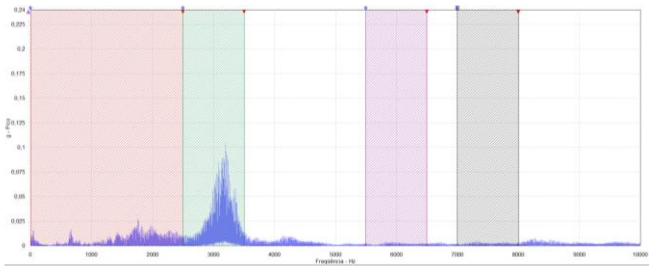

**Figure 9. 7.6:1 | Frequency Spectrum | 10,000 Hz.**

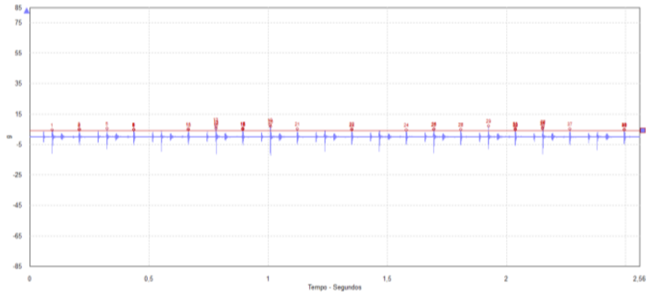

**Figure 10. 7.6:1 | Time-Domain Signal | 10,000 Hz.**

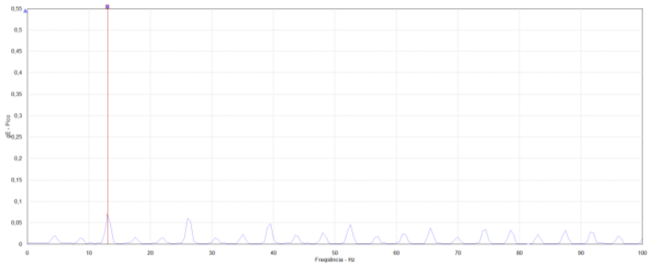

**Figure 11. 7.6:1 | Envelope Spectrum | 100 Hz.**

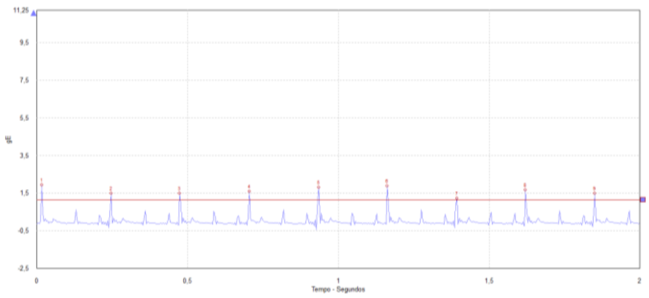

**Figure 12. 7.6:1 | Envelope Time-Domain Signal | 100 Hz.**

Figures 13 to 16 display the vibrational behavior of the BASF engine operating at a compression ratio of 8.2:1, a condition in which the first signs of knock are observed, becoming more pronounced at a ratio of 8.6:1.

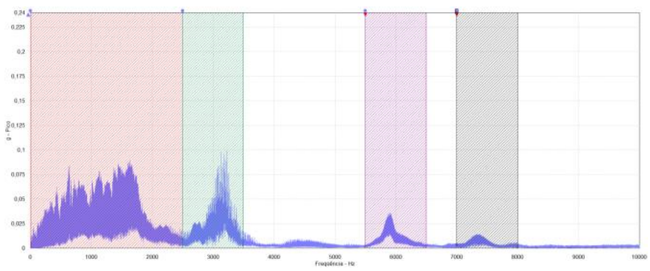

**Figure 13. 8.2:1 | Frequency Spectrum | 10,000 Hz.**

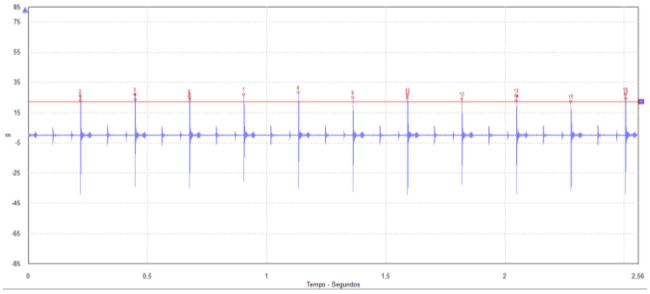

**Figure 14. 8,2:1 | Time-Domain Signal | 10,000 Hz.**

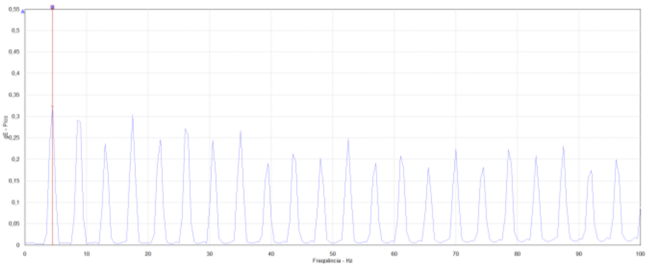

**Figure 15. 8.2:1 | Envelope Spectrum | 100 Hz.**

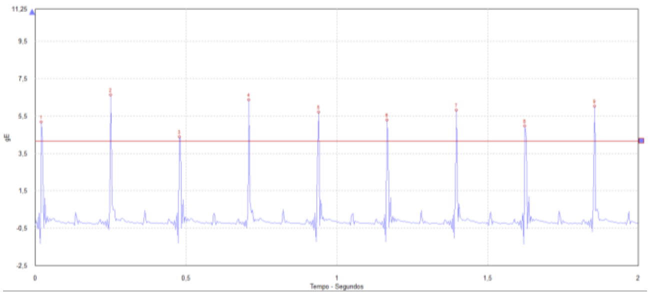

**Figure 16. 8.2:1 | Envelope Time-Domain Signal | 100 Hz.**

Figures 17 to 20 illustrate the vibrational behavior of the engine operating at a compression ratio of 8.6:1, under detonation, highlighting the dynamic response characteristics associated with this abnormal combustion condition.

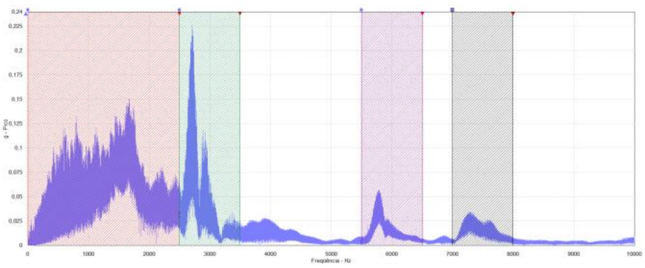

**Figure 17. 8.6:1 | Frequency Spectrum | 10,000 Hz.**

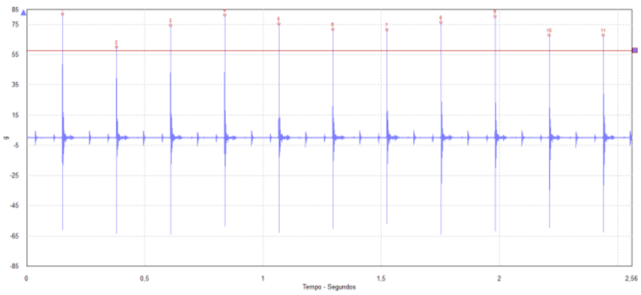

**Figure 18. 8.6:1 | Time-Domain Signal | 10,000 Hz.**

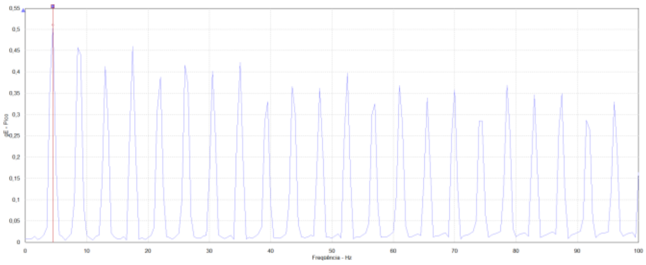

**Figure 19. 8.6:1 | Envelope Spectrum | 100 Hz.**

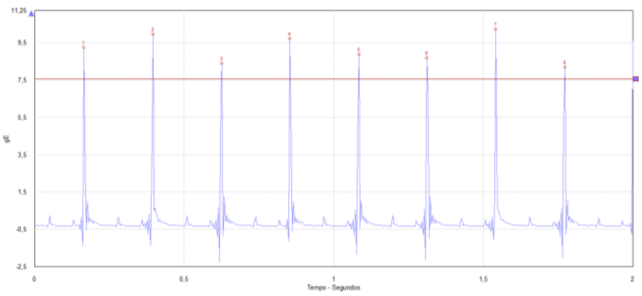

**Figure 20. 8.6:1 | Envelope Time-Domain Signal | 100 Hz.**

Peaks with increasing amplitudes were observed in the 0 to 2500 Hz range, indicating the predominant influence of dynamic forces from the combustion process. Moreover, a significant intensification of peaks was detected in the 2500 to 3500 Hz range - an inherent characteristic of engine operation, but with substantially higher amplitudes under knock conditions. Additional peaks were identified in the 5400 to 6500 Hz and 7000 to 8000 Hz ranges.

The time-domain analysis of the vibrational signals revealed peaks with a time interval (ΔT) corresponding to the period of the combustion frequency, estimated at approximately 4.5 Hz for the BASF engine at the analyzed operating speed. These peaks are associated with the acceleration generated by the piston impact at top dead center (TDC), a characteristic event of the combustion cycle. The intensity of these peaks was found to be higher under knock conditions, reflecting the abrupt release of energy during knocking combustion.

In addition, the envelope technique was applied to extract the envelope of the time-domain signal, highlighting amplitude variations associated with the combustion frequency (4.5 Hz). The results demonstrated that, under knock conditions, the peak corresponding to the combustion frequency exhibited a significantly higher amplitude than the other signal components, clearly standing out from normal combustion conditions.

Figure 21 shows the Frequency Spectrum for the analyzed compression ratios. For the 7.6:1 ratio, high repeatability is observed, with consistent peak amplitudes in the 0 to 2500 Hz and 2500 to 3500 Hz bands, reflecting stable combustion. For the 8.6:1 and 8.0:1 ratio, the graphs reveal a significant increase in amplitudes in the 2500 to 3500 Hz, 5500 to 6500 Hz, and 7000 to 8000 Hz bands, with close overlap between the data sets. The envelope spectra shown in Figure 22 reveals a marked increase in amplitudes, particularly at 4.5 Hz, as the compression ratio increases.

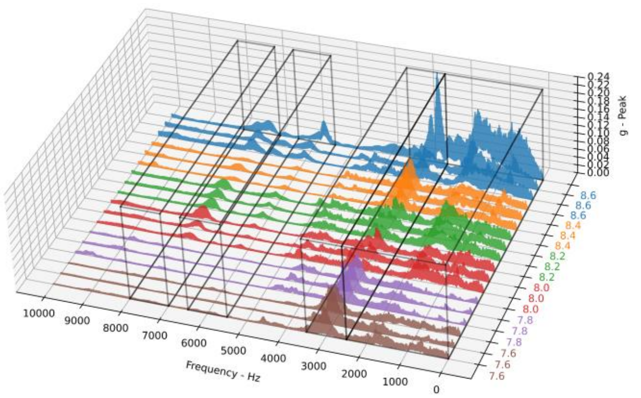


**Figure 21. Frequency Spectrum at 10,000 Hz for each compression ratio (7.6:1 to 8.6:1).**

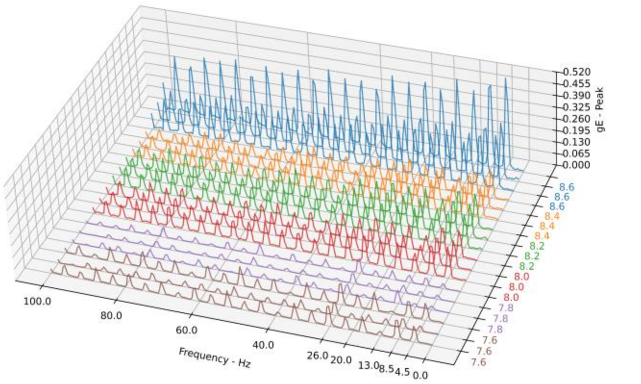


**Figure 22. Envelope Spectrum for each compression ratio (7.6:1 to 8.6:1).**

Figures 23 and 24 present the time-domain signals corresponding to the raw and envelope-processed data, respectively. These signals illustrate the evolution of peaks associated with piston impact at top dead center (TDC), with a time interval (ΔT) corresponding to the period of the combustion frequency (4.5 Hz).

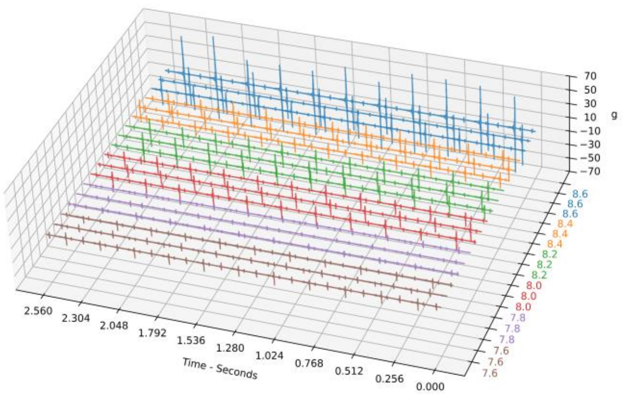


**Figure 23. Time-Domain Signal at 10,000 Hz for each compression ratio (7.6:1 to 8.6:1).**

The results show a progressive reduction in peak amplitude as the compression ratio decreases from 8.6:1 to 7.6:1, reflecting the lower energy released during normal combustion compared to knocking conditions.

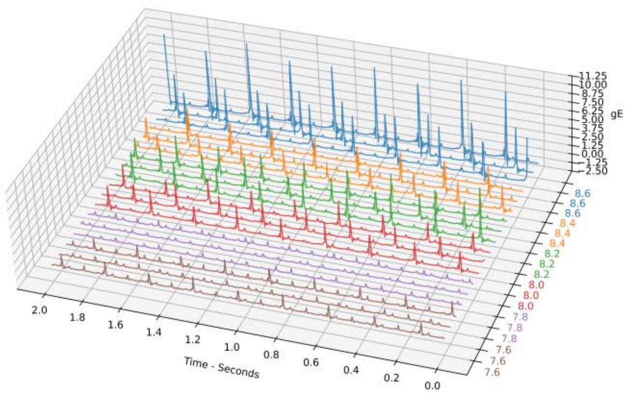


**Figure 24. Envelope Time-Domain Signal for each compression ratio (7.6:1 to 8.6:1).**

The quantitative results used to compare the collected data are presented below. Figures 25 and 26 show the maximum amplitudes identified within the time intervals (ΔT) corresponding to the period of the combustion frequency in each time-domain signal, along with the overall average calculated for each compression ratio in each acquisition.

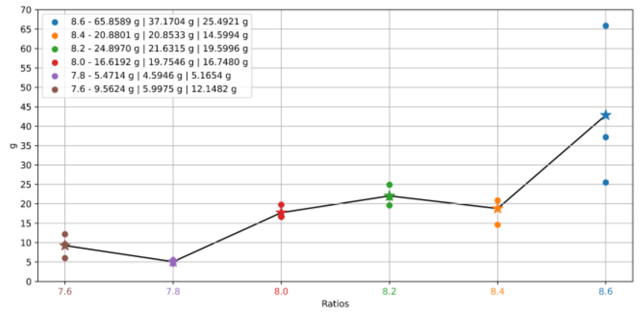


**Figure 25. Maximum amplitude in the Time-Domain Signal obtained from three acquisitions for each compression ratio.**

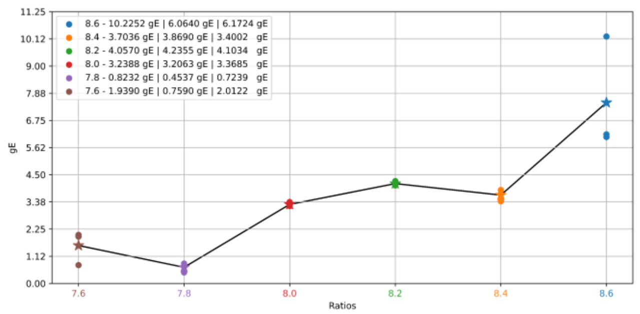


**Figure 26. Maximum amplitude in the Envelope Time-Domain Signal obtained from three acquisitions for each compression ratio.**

Based on the Frequency Spectra obtained through the Fast Fourier Transform (FFT), Figures 27 to 30 present the highest recorded amplitudes in each frequency range of interest. Figure 31 shows the amplitudes at 4.5 Hz in the Envelope Spectrum.

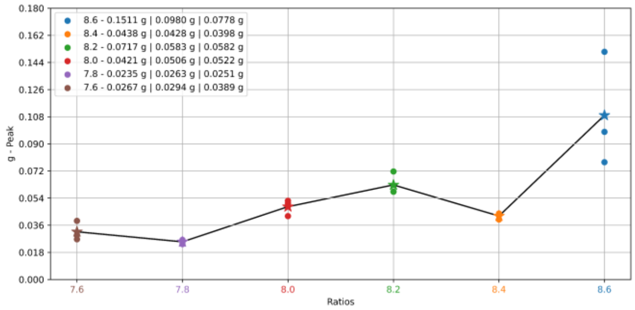


**Figure 27. Maximum amplitudes in the Frequency Spectrum (0 - 2500 Hz) for each compression ratio.**

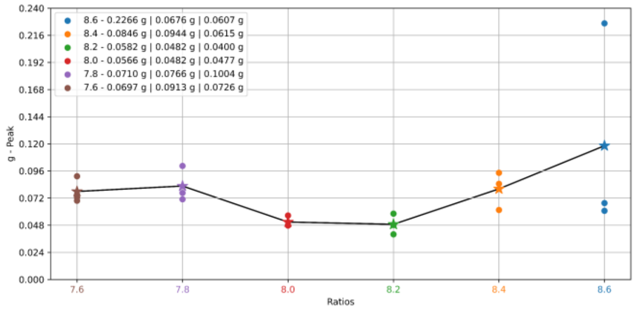


**Figure 28. Maximum amplitudes in the Frequency Spectrum (2500 - 3500 Hz) for each compression ratio.**

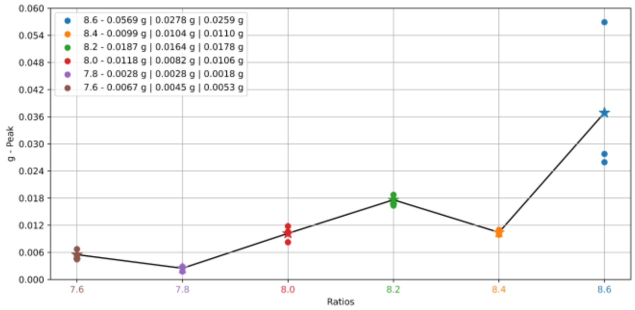


**Figure 29. Maximum amplitudes in the Frequency Spectrum (5500 - 6500 Hz) for each compression ratio.**

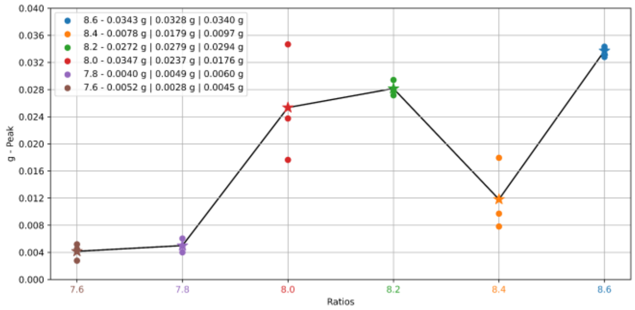


**Figure 30. Maximum amplitudes in the Frequency Spectrum (7000 - 8000 Hz) for each compression ratio.**

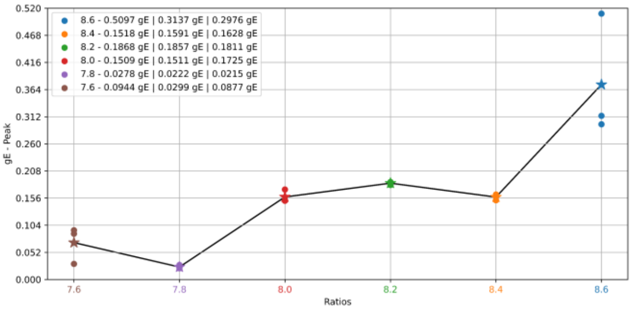


**Figure 31. Amplitude at 4.5 Hz for each compression ratio | Envelope Spectrum.**

To investigate the influence of ethanol hydrated quantity in the fuel mixture on the vibrational behavior of the BASF engine, two independent trials were conducted for each ethanol hydrated percentage tested (16 ml, 18 ml, 19 ml, 20 ml, and 21 ml) at a compression ratio of 8.6:1. Figures 32 to 35 present 3D graphs illustrating the engine's vibrational behavior for different ethanol contents.

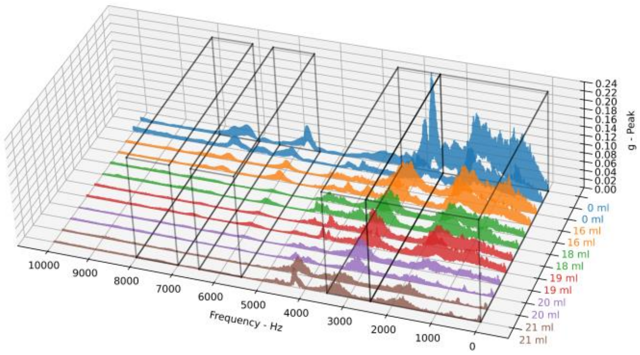


**Figure 32. Frequency Spectrum at 10,000 Hz for each ethanol volume (0, 16, 18, 19, 20, 21 ml).**

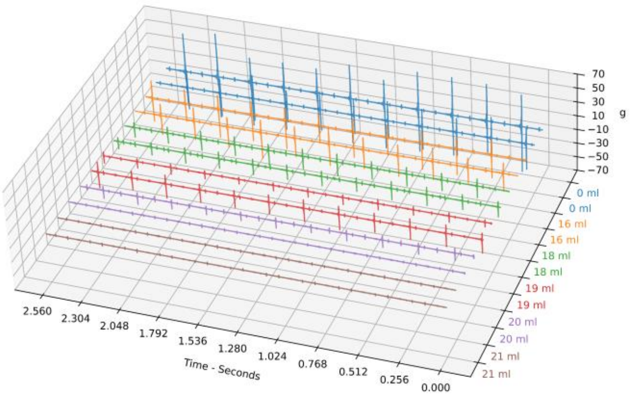


**Figure 33. Time-Domain Signal at 10,000 Hz for each ethanol volume (0, 16, 18, 19, 20, 21 ml).**

At 16 ml of ethanol hydrated, high repeatability between acquisitions is observed, with consistent peak amplitudes in the 0 to 2500 Hz, 5500 to 6500 Hz, and 7000 to 8000 Hz ranges, indicating the presence of milder knock. As the ethanol hydrated volume increases, a gradual decrease in amplitudes is observed, suggesting the onset of combustion stability.

At 21 ml, the graphs show a significant absence of peaks in the 2500 to 3500 Hz, 5400 to 6500 Hz, and 7000 to 8000 Hz ranges, with high consistency between the two acquisitions, indicating more uniform and stable combustion like the engine operating at a 7.6:1 compression ratio, as shown in Figures 9 to 12.

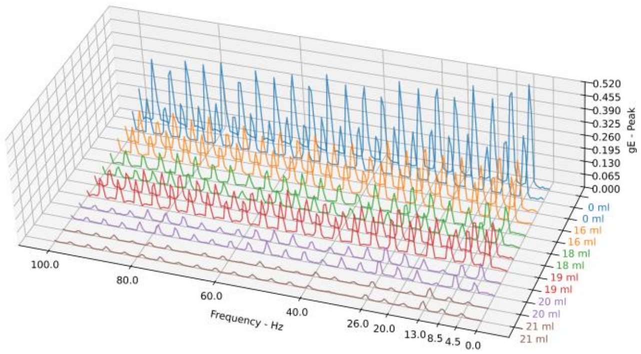


**Figure 34. Envelope Spectrum for each ethanol volume (0, 16, 18, 19, 20, 21 ml).**

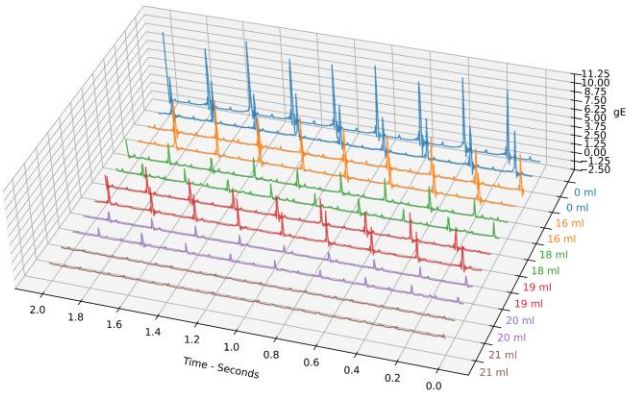


**Figure 35. Envelope Time-Domain Signal for each ethanol volume (0, 16, 18, 19, 20, 21 ml).**

With the increase in ethanol hydrated content in the mixture, a trend toward stabilization of vibrational levels was observed, especially at 20 ml and 21 ml. Figures 36 and 37 present the maximum amplitudes identified within the time intervals (ΔT) corresponding to the period of the combustion frequency in each time-domain signal, along with the overall average for each ethanol hydrated variation in the mixture (in ml).

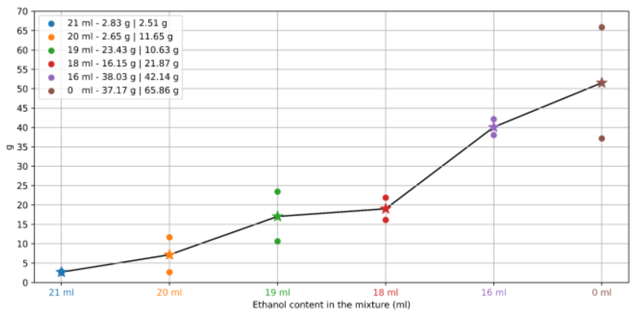


**Figure 36. Maximum amplitude in the Time-Domain Signal for each ethanol volume (0, 16, 18, 19, 20, 21 ml).**

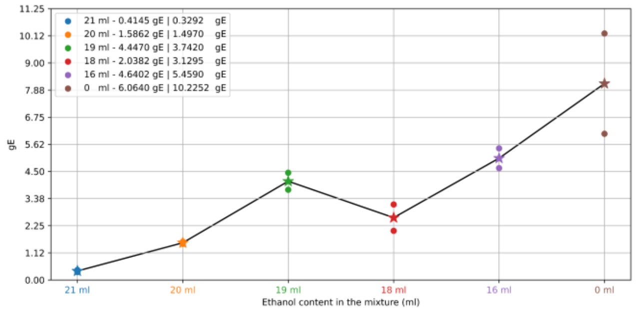


**Figure 37. Maximum amplitude in the Envelope Time-Domain Signal for each ethanol volume (0, 16, 18, 19, 20, 21 ml).**

Figures 38 to 41 show the highest amplitude recorded in each frequency range of interest. Figure 42 presents the amplitudes at 4.5 Hz in the Envelope Spectrum.

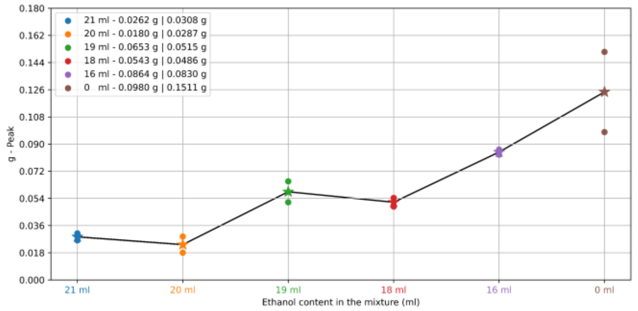


**Figure 38. Maximum amplitudes in the Frequency Spectrum (0-2500 Hz) for each ethanol volume (0, 16, 18, 19, 20, 21 ml).**

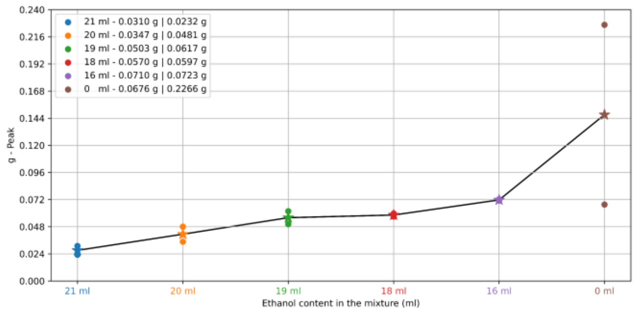


**Figure 39. Maximum amplitudes in the Frequency Spectrum (2500-3500 Hz) for each ethanol volume (0, 16, 18, 19, 20, 21 ml).**

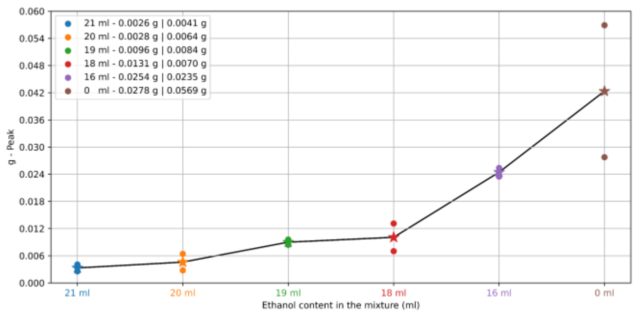


**Figure 40. Maximum amplitudes in the Frequency**

**Spectrum (5500-6500 Hz) for each ethanol volume (0, 16, 18, 19, 20, 21 ml).**

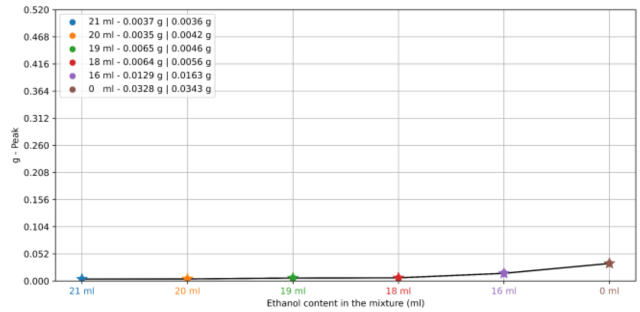


**Figure 41. Maximum amplitudes in the Frequency Spectrum (7000-8000 Hz) for each ethanol volume (0, 16, 18, 19, 20, 21 ml).**

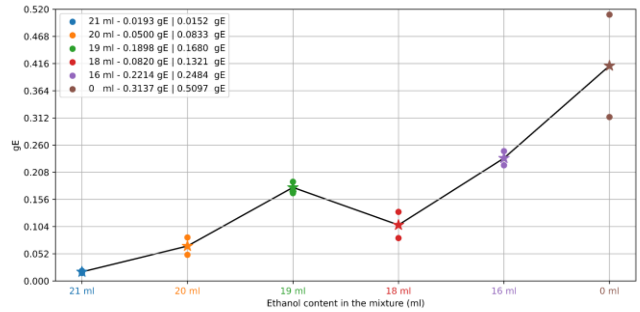


**Figure 42. Amplitude at 4.5 Hz for each ethanol volume (0, 16, 18, 19, 20, 21 ml) | Envelope Spectrum.**

The vibrational signature of the engine under knock-free conditions, obtained by adding 21 ml of ethanol hydrated to 100 ml of regular gasoline, closely resembled the reference established with gasoline at a compression ratio of 7.6:1, considered the standard for stable combustion. This similarity was evidenced by the reduction in vibrational amplitudes, the disappearance of frequencies in the 7000 to 8000 Hz range, and the absence of time-domain peaks associated with the characteristic combustion frequency around 4.5 Hz.

The results indicated an increase in knock intensity with the rise in compression ratio. At 7.6:1 and 7.8:1, no signs of knock were observed, characterizing stable combustion. Initial indications of knock emerged at 8.0:1, with a significant intensification at 8.6:1, particularly when compared to the 7.6:1 reference condition using ethanol-free gasoline. A substantial rise in vibrational amplitudes across the frequency ranges of 0-2500 Hz, 2500-3500 Hz, 5500-6500 Hz, and 7000-8000 Hz served as clear evidence of this behavior. In addition, more pronounced time-domain peaks were observed, with intervals (ΔT) corresponding to the engine's combustion frequency, approximately 4.5 Hz.

The source of this vibrational behavior is associated with the formation of shock waves in the combustion chamber during knock. These waves excite specific vibrational modes of the engine, leading to characteristic patterns that can be detected through spectral and time-domain analysis. These findings indicate that the compression ratio is a critical factor in combustion dynamics, directly influencing the occurrence of knock occurrence.

## 5. CONCLUSION

As the ethanol hydrated concentration in the fuel mixture increased, a progressive reduction in vibration levels was observed. The analysis revealed that the addition of 21 ml of ethanol hydrated to 100 ml of Brazilian regular gasoline resulted in the complete suppression of knock, even at the highest tested compression ratio (8.6:1). This effect was corroborated by spectral and temporal analyses, which indicated a significant reduction in vibrational amplitudes in the frequency bands associated with knock, culminating in uniform and stable combustion. Comparisons with the reference condition (7.6:1, without knock) confirmed that ethanol hydrated addition enables achieving vibrational patterns similar to those observed under ideal combustion conditions, even at higher compression ratios.

The integration of spectral, temporal, and quantitative analyses provided a robust characterization of the vibrational signature of the BASF engine. The amplitude patterns in the analyzed frequency bands, combined with the repeatability of temporal peaks, constitute a valuable tool for monitoring engine performance under different operating conditions and fuel compositions. These findings open perspectives for the development of real-time diagnostic systems capable of detecting and mitigating the risks associated with knock in internal combustion engines. Furthermore, the results suggest that precise adjustments in fuel formulation and compression ratios can optimize energy efficiency, reduce unwanted vibrations, and minimize structural damage, contributing to the advancement of more sustainable and reliable engine technologies.

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