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Acoustic source identification and knock detection in a Wankel engine operating on gasoline and hydrogen fuels

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This study presents an experimental investigation into the acoustic emissions of a Wankel rotary engine fueled by three distinct injection strategies: unleaded gasoline (E10), hydrogen with water addition (H_2W), and pure hydrogen (H_2). Measurements were carried out on an engine test bench under steady-state operating conditions. The analysis encompassed both sound pressure levels and frequency-domain characteristics of the acoustic signals. A microphone array in conjunction with CAE Noise Inspector software was used to capture and analyse noise emissions originating from the combustion chamber. The results revealed distinct variations in acoustic behaviour depending on the fuel type. Notably, the engine powered by pure hydrogen exhibited the highest amplitude of emitted combustion noise, potentially attributable to knocking combustion phenomena. The study underscores that fuel selection has a significant impact on the acoustic signature of the Wankel engine. Furthermore, the adopted measurement methodology proved effective in identifying combustion-related sound patterns and provides a foundation for future optimisation of rotary engines operating on alternative fuels.

Key words: *Wankel, knocking, noise, sound, hydrogen*

1. Introduction

The Wankel engine, due to its unique rotary piston design, is an interesting alternative to conventional piston engines. Its advantages, such as high-power output at a compact size and smooth operation, make it applicable in various fields of technology. In recent years, the growing interest in alternative fuels, including hydrogen, has led to intensive research into the use of this gas as an environmentally friendly energy source for internal combustion engines. Both of these considerations make the use of an alternative fuel such as hydrogen for a Wankel engine a legitimate challenge. In such a case, one of the problems to be solved is the occurrence of knock combustion during the operation of the power unit. Knock combustion in internal combustion engines was first described by Harry Ricardo. This undesirable phenomenon involves the premature ignition of the fuel-air mixture due to contact with the superheated walls of the combustion chamber. An analysis of the scientific literature reveals that the problem of knock combustion is the subject of intensive research not only in Wankel engines. The literature points to various methods of detecting this phenomenon, including the analysis of pressure pulsations in the combustion chamber, the measurement of mechanical vibrations of engine components, and the use of advanced diagnostic systems. In particular, amplitude-frequency analysis makes it possible to precisely determine the intensity and characteristics of knock combustion, so that measures can be taken to eliminate it. In spark-ignition (SI) engines, knocking combustion manifests itself in high-frequency pressure pulsations, which can lead to mechanical damage and reduced efficiency of the power unit [24].

Knock combustion, as a result, can lead to negative consequences for engine operation [9]. The causes of knock combustion, such as abnormal ignition, high temperature and pressure in the combustion chamber, allow the selection of appropriate detection and control methods. It is also worth emphasising the importance of optimising the combustion process to prevent knock combustion and ensure proper engine operation.

One of the main parameters affecting the formation of knock combustion is the temperature occurring in the combustion chamber [16]. Higher temperatures can increase the propensity for this phenomenon to occur. Currently, the mechanisms of knock combustion initiation under different thermal conditions are being analysed to better understand this complex process. The results of the research indicate that the temperature in the combustion chamber must be controlled to minimise the risk of knocking combustion.

As pressure and temperature increase, the mixture may self-ignite at specific points in the combustion chamber. These self-ignition points interact with the flame front in an uncontrolled manner, causing pressure and temperature oscillations. The rapidly changing pressure amplitude can lead to potential engine damage [6, 32]. The process of knock initiation, recorded using a camera for recording rapidly changing phenomena, is shown in the Fig. 1.

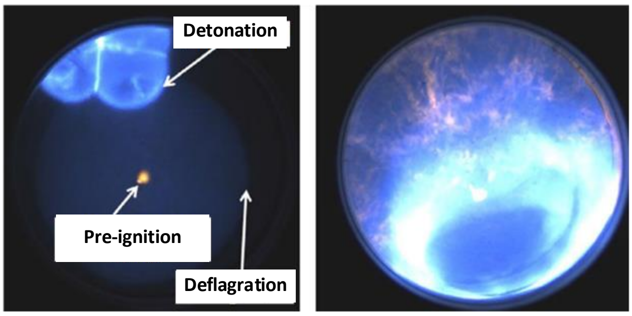

Fig. 1. Screenshots from the recording of rapidly changing measurements for engine operation with knocking combustion [15]

Wankel engines are characterised by a rather specific combustion process due to their design. The tendency for knocking combustion in a Wankel engine differs from that in piston engines, which means that current research on hydrogen combustion may not be directly applicable to this type of engine. Therefore, research on hydrogen combustion in piston engines is more common, but its results are not easily transferable to Wankel engines. [1, 2, 5, 14, 21, 26].

The occurrence of knocking combustion is also influenced by other engine operating parameters such as engine speed, engine load and the composition of the fuel-air mixture [17]. The available experimental results allow us to determine the optimal engine operating conditions that minimise the risk of knock combustion. The importance of precise control of the combustion process to ensure stability and efficiency should be emphasised here.

For example, the authors of the article [20] presented a way to improve the efficiency of a spark-ignition engine with an increased compression ratio. They proposed to counteract knocking combustion by dosing fuel with an increased octane number. The publication also presents the idea of measurements, the test stand and the results obtained. Changing from traditional fuel to hydrogen fuel can affect the intensity of the combustion process. The specific properties of hydrogen that distinguish it from traditional hydrocarbon fuels reveal the potential benefits and challenges of using hydrogen as a fuel in internal combustion engines, including its impact on knocking combustion. The publication [18] highlights the need to adapt engine design and operating parameters to the specifics of hydrogen combustion.

It is not only hydrogen that affects the possibility of knock combustion. The paper [27] presents a preliminary study of the intensity of knock combustion in a large methanol engine. The effectiveness of five conventional indicators of knock combustion intensity (MAPO, IMPO, AE, MVTD, and HRR) was examined at 50%, 75% and 87.5% load of a methanol-hydrogen engine with an average speed. The MAPO index was shown to be the most suitable for knock combustion analysis.

Various methods are used to detect knock combustion in internal combustion engines. The article [12] describes a simple knock combustion sensor tester. The article also presents information that most knock combustion processes oscillate in frequency ranges from 5000 to 15,000 Hz, and the presented sensor can record up to 37,000 Hz.

Another method is presented in the article [3], where the concept of using low-cost and readily available Arduino microprocessor modules and the Matlab computing package to detect knocking combustion in spark-ignition engines is presented. The tests were carried out for a typical range of vibration frequencies characteristic of knock combustion. The tests were performed for two piezoelectric sensors with linear characteristics, which indicated the need for signal amplifiers in the target measurement system. According to the authors, the measurement methods used cannot satisfactorily handle the piezoelectric sensors used. Sampling frequencies of microprocessor modules communicating directly with Matlab software turned out to be much lower than the hardware capabilities. This justifies the need to use another type of method for detecting knock combustion, such as a microphone array.

On the other hand, the article [10] presented a method for the detection of knock combustion in gasoline engines based on the Hilbert-Huang transformation. This analysis technique allowed the decomposition of the signal into individual components, which enabled precise information about the combustion process. Analysis of the pressure signal using the Hilbert-Huang transform allowed accurate monitoring and evaluation of the combustion process of the fuel-air mixture.

Another method used to analyse knock combustion is the use of the optical signal from the combustion chamber. The article [23] presents research conducted on a modified single-cylinder engine equipped with an optical sensor with direct access to the combustion chamber. Spectral analysis of the flame in the combustion chamber, taking into account chemiluminescence phenomena, made it possible to assess the intensity of knock combustion. The results confirmed the possibility of detecting and evaluating the intensity of knock combustion based on optical signal analysis.

Sound recording methods of internal combustion engines are also used to detect and analyse the phenomenon of knock combustion. They make it possible to evaluate the intensity of knock combustion. Acoustic methods are widely used in the analysis of internal combustion engines. The article [25] presents an acoustic analysis of a single-cylinder diesel engine using magnetised blends of biodiesel and diesel fuel. The effect of biodiesel percentage (0; 5; 10 and 20%) and magnetic field strength (0; 5300 and 7000 G) on engine noise was studied. The results of the analysis of variance confirmed significant differences between the tested fuel blends and magnetic levels at the 1% probability level.

On the other hand, the article [30] proposes a method for the separation and identification of diesel engine noise sources, which combines the binaural noise localisation method and the blind source separation method. The method can effectively separate and identify combustion noise and piston impact noise of a diesel engine. The results show that the frequency of combustion noise and piston impact noise are concentrated at 4350 Hz and 1988 Hz, respectively. Compared with the blind source separation method, the proposed method has better separation and identification results, and the separation results have fewer interfering components from other noises.

An interesting idea for acoustic analysis is the method presented in the article [7], where the correlation between airborne sound and structure-borne sound in a diesel engine was analysed. It was shown how structure-borne sound signals can be used to evaluate engine noise. The study showed a high correlation between airborne sound and structure-borne sound. The article suggests that analysis of structure-borne sound can be useful in diesel engine management systems for noise control.

As mentioned earlier, there are also publications describing the correlation between knock combustion and combustion noise. The article [31] describes a correlation method based on time-frequency masking theory. The proposed method simultaneously takes into account the effects of time and frequency masking, which allows for a more accurate analysis of knock noise. The method has been successfully applied to the objective evaluation of diesel engine knock noise and verified by subjective evaluation. The results of the study show the potential of the new method in the objective evaluation of the noise quality of diesel engines.

Some authors also present methods for diagnosing engine damage based on noise intensity analysis. In the publication [29], the noises of an EFI gasoline engine in normal and damaged states were measured, and their sound intensity level (SIL) contours were calculated by interpolation to preliminarily investigate the possibility of SIL-based EFD. An incomplete WPA model consisting of a five-level discrete wavelet transform (DWT) and a four-level WPA was developed and applied to the measured noise signals to extract engine damage features. A multi-layer ANN model was used to classify engine damage using the extracted noise features. The results presented here suggest that noise-based WPA-ANN models are effective for engine damage diagnosis.

Changing the fuel also affects the combustion noise emitted by a working engine. The paper [22] investigated the combustion noise characteristics of a diesel engine with hydrogen added to the intake air. The noise of the engine with 10 % vol. hydrogen added to the intake air was lower than that of the engine with diesel alone at late fuel injection times. A transient combustion noise generation model was introduced to discuss the noise characteristics based on the conversion of energy from combustion impact to noise through structural vibration. The results showed that maximum combustion impact energy had a dominant effect on maximum engine noise power for each cycle.

On the other hand, the paper [11] investigated the combustion noise characteristics of hydrogen reciprocating engines, in which the authors found an opportunity to reduce combustion noise. The results showed that increasing the air-fuel equivalence ratio, ignition delay, and exhaust gas recirculation ratio produced favourable acoustic effects, with the air-fuel equivalence ratio being the most effective, with a possible noise reduction of up to 20 dB.

In summary, the identification of the combustion noise amplitude of knock combustion in a hydrogen-powered Wankel engine is a key aspect in the context of monitoring and optimising the combustion process of such a power unit. However, the use of hydrogen presents several technological challenges, one of the most serious of which is the phenomenon of knocking combustion [4]. In the case of hydrogen-powered Wankel engines, this problem becomes even more complex due to hydrogen's specific properties, such as high combustion velocity and propensity for self-ignition [28].

This article presents the results of a study on identifying the amplitude of the sound of knocking combustion in a hydrogen-powered Wankel engine. This research was based on the analysis of the amplitude and frequency of sounds recorded in real time at constant engine operating conditions. Based on the data obtained, an evaluation was made of the primary and alternative fuels on the intensity of the sound amplitude. Further parts of the article include a detailed description of the research methodology, analysis of the results obtained and conclusions regarding the possibility of the occurrence of knock combustion in a Wankel engine.

2. Methodology

2.1. Engine description

The object of the study was the Aixro XR 50 Wankel engine (Fig. 2). It is a naturally aspirated, four-stroke, spark-ignition engine offered by the German company Aixro GmbH. It is a single-rotor four-stroke unit with a displacement of 294 cm^3. It achieves a power equal to 33 kW (for a rotational speed of 8750 rpm), the maximum torque produced by the engine is 39 Nm (for a rotational speed of 7500 rpm), and the permissible rotational speed is 10,800 rpm. At the factory, the manufacturer equips the engine with a carburettor power system and a magnetoinduction ignition system with a fixed ignition advance angle. The basic technical parameters of the engine are shown in Table 1.

Table 1. Basic technical data of the research engine [8]

Parameter	Value	Unit
Manufacturer/designation	AIXRO GmbH / XR50	–
Type	4-stroke with a single rotor	–
Max. power (8750 rpm)	33	kW
Max. torque (4500 rpm)	35	Nm
Max. speed	11,000	rpm
Combustion chamber capacity	294	cm^3
Ignition type	Magneto ignition with a fixed timing	–
Fuel	Automotive gasoline with a 2% addition of lubricating oil	–
Mass	17	kg

To carry out the tests, the power unit was fueled with the original fuel (motor gasoline) and hydrogen gas. Therefore, the engine was equipped with additional systems. Here we can distinguish: a system of indirect injection into the intake manifold, both original fuel and hydrogen fuel, and a lubricating oil metering system (the factory engine was fed with a mixture of lubricating oil and fuel). The magnetoinductive ignition system was replaced by an electronic ignition system. The engine was also retrofitted with an electronically controlled throttle and a water injection system for the intake manifold. An electronic ECU was also developed to integrate the measurement sensors installed on the test unit and to precisely control the actuators. To precisely dispense the gaseous fuel, a hydrogen supply system was developed. This system consisted of a battery of gaseous fuel storage tanks, three stages of pressure reduction from 200 to 1 bar (due to the remote location of the tank battery from the test facility), a fuel storage tank, a fuel mass flow meter and a fuel injector. A water injection system was also developed for the intake manifold of the test facility. This system consisted of a demineralised water tank, a pump, a pressure regulator and an injector. The coolant was injected into the intake manifold, just after the air throttle and the gasoline and hydrogen injectors. The test stand with the AIXRO XR50 engine installed allows full calibration and adjustment of the fuel supply, lubrication, and ignition systems.

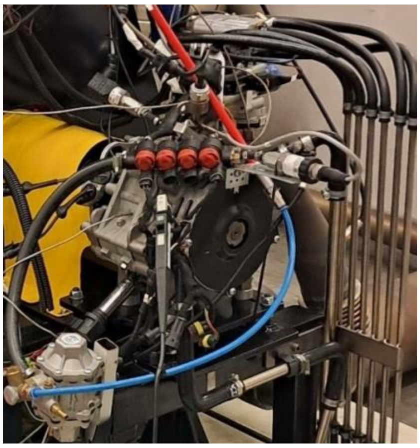

Fig. 2. AIXRO XR50 engine on the test bench

2.2. Acoustic camera

The approach used for measuring noise sources involved utilising the Noise Inspector software in conjunction with an acoustic camera provided by CAE Systems & Software. This sophisticated equipment transforms sound into visual representations, such as images or videos. Through this method, noise-emitting sources become distinguishable and their precise locations can be swiftly identified [9]. Thanks to this visual representation, the identification of noise origins can occur in real-time. The system is adept at both detecting noise sources and quantifying their intensity in terms of emitted sound pressure. By visualising noise sources in images or videos, the time required for measurements is substantially reduced compared to traditional methods [13]. The apparatus comprises an array of 16 microphones arranged in a single plane, with an HD camera centrally positioned (Fig. 3). Additional components include modules for signal and image processing. The entire system is linked to a portable computer. A diagram of the entire test setup is shown in Fig. 4.

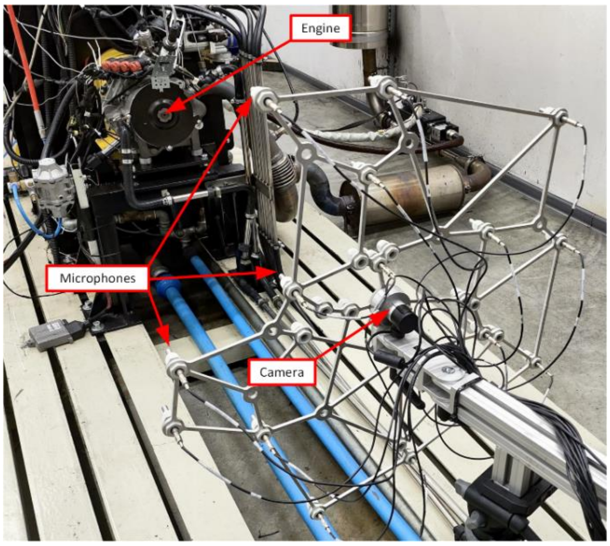

Fig. 3. Engine and acoustic camera

Key components of the Noise Inspector system are [19]:

- microphone array
- Microsoft LifeCam Studio 1080p HD camera
- 16 G.R.A.S. 40PH one-dimensional microphones
- ICP data acquisition module PXIe-1073 from National Instruments
- PXI-4496 measurement card
- portable computer
- CAE Noise Inspector V6.0 software.

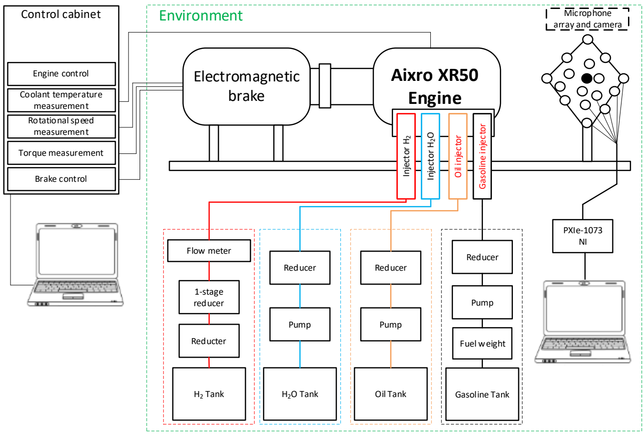

Fig. 4. Measurement station diagram

This measurement technique offers exceptional convenience. The modular architecture of the Noise Inspector system ensures adaptability to meet specific requirements. Notable benefits of the acoustic camera include [19]:

- a single measurement suffices, eliminating the need for multiple readings
- greater accuracy compared to conventional measuring microphones
- non-intrusive operation, allowing measurements without disrupting equipment functionality (e.g., in industrial environments)
- rapid measurement process, typically taking only a few minutes
- generation of noise source maps, facilitating identification of unwanted noise origins
- capability to pinpoint specific system components responsible for noise and assess noise levels
- no requirement for work stoppages at the measurement location
- effective identification of noise sources even in reverberant settings
- suitability for both indoor and outdoor measurements.

The fundamental working principle of the acoustic camera system involves capturing noise sources across different acoustic levels. A unique feature of this system is its ability to adjust the focus level after the measurement, enabling the production of multiple acoustic images without the need for repeated measurements. Furthermore, the live preview function offers immediate access to preliminary measurement data in real-time [13].

2.3. Measurement conditions

The test plan included performing tests at three different engine operating conditions labelled sequentially:

- E10 – feeding with unleaded 95 gasoline
- H_2W – hydrogen feed with water added
- H_2 fueling with pure hydrogen.

The second power strategy concerned hydrogen fueling with the addition of water, i.e. to lower the combustion temperature of the mixture and thus mitigate the process of knocking combustion, a water injection map was developed when fueling with hydrogen to maximise the use of the gaseous fuel – to obtain the highest possible mechanical power generated by the engine. The third strategy involved feeding pure hydrogen with no water input.

Three separate noise recordings (3 seconds each) were made for each trial, following one after the other. In addition, the noise of the accessories when the engine was turned off (electro-brake, ventilation, stand cooling, etc.) was recorded in a separate trial.

The tests were performed for engine operating parameters:

- speed 5000 rpm
- torque of 10 Nm
- hydrogen flow in H_2W and H_2 tests 290 l/min.

In all tests, the engine was in the same thermodynamic state. The tests were performed at short intervals, which eliminated the influence of external factors. The acoustic camera was 1.1 meters away from the engine.

3. Research results

Figure 5 shows the average value of noise amplitude as a function of its frequency. The curves represent 3 different supply conditions of the Wankel engine E10, H_2W, and H_2 (each averaged from three separate samples). For the analysis, four frequency ranges were selected in which the greatest difference in noise amplitudes is noticeable, and at the same time, the source of the noise comes from the engine:

- 4000–6000 Hz
- 6000–8000 Hz
- 8000–12,000 Hz
- 12,000–22,000 Hz.

Fig. 5. Average value of noise amplitude as a function of its frequency for three different engine operating conditions

Ranges below 4000 Hz were discarded because no significant difference in the noise amplitude waveform for different samples was noticed there. The maximum value that was analysed was also limited to 22,000 Hz, because the higher frequency range of noise is inaudible to humans. Figure 3 also shows the noise of accessories (electro-brake cooling, ventilation, etc.) recorded when the engine was not running.

To further visualise the differences presented in Fig. 5, a plot of Fig. 6 was made showing the differences in sound amplitude values, respectively, between the

- H_2W supply, and E10 supply
- H_2 supply, and H_2W supply.

As can be seen in Fig. 6, the differences between H_2W and E10 supply are not as large as those between H_2 and H_2W supply. When switching from E10 to H_2W fuel, a reduction in noise amplitude is noticeable in the range of 4000 to 12,000 Hz. On the other hand, an increase in noise amplitude occurred in the range of 12,000 to 22,000 Hz. The situation is different when changing from H_2W fuel to H_2. In this case, an increase in noise amplitude was noticed in all four tested ranges from 4000 to 22,000 Hz, by about a maximum of 6 dB.

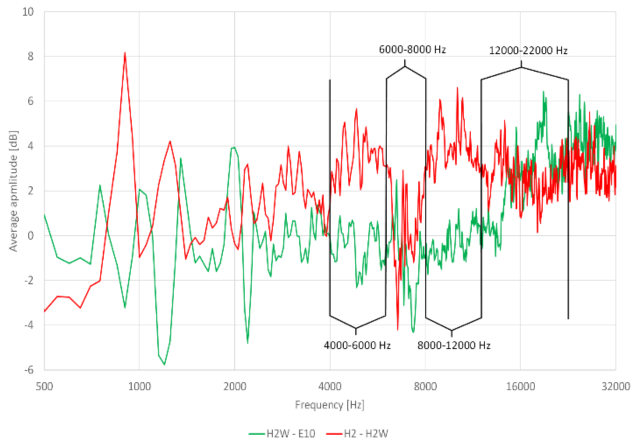

Fig. 6. Variations in the average value of noise amplitude as a function of its frequency for three different engine operating conditions

To highlight these differences, an additional analysis was performed showing the exact average values of the noise amplitude in each range and for each type of fuel supply. Figure 7 shows a larger value of the average amplitude for the H_2 supply in the ranges from 4000–6000 and 8000–22,000 Hz. On the other hand, in the frequency range of 6000–8000 Hz, the E10 supply has the highest value of average amplitude. Figure 7 also indicates the value of the standard deviation from the three trials conducted for each engine supply strategy.

The pure hydrogen supply (H_2) generates the highest combustion noise emissions in the ranges: 4000–6000 Hz, 8000–12,000 Hz, and 12,000–22,000 Hz, reaching maximum values of 86.55 dB, 76.31 dB, and 68.83 dB, respectively (Fig. 7). This indicates a rather dynamic course of heat generation in the engine combustion chamber.

Since the trend of increased noise amplitude for the H_2 supply is noticeable from the previous results, it was also decided to analyse the maximum noise values. Figure 8 shows the maximum noise values recorded during each test.

The difference in the amplitude level of the H_2 supply is also evident in this parameter.

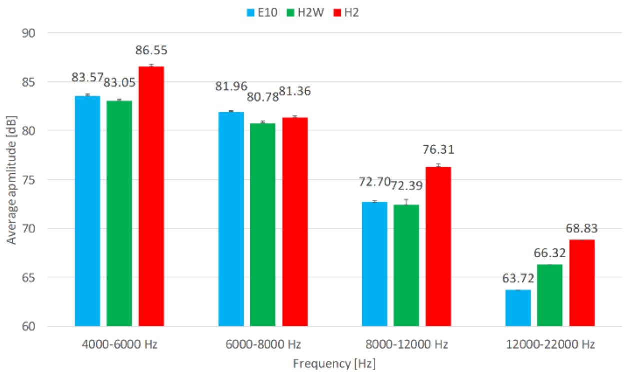

Fig. 7. Average value of noise amplitude for selected frequency ranges for three different engine operating conditions

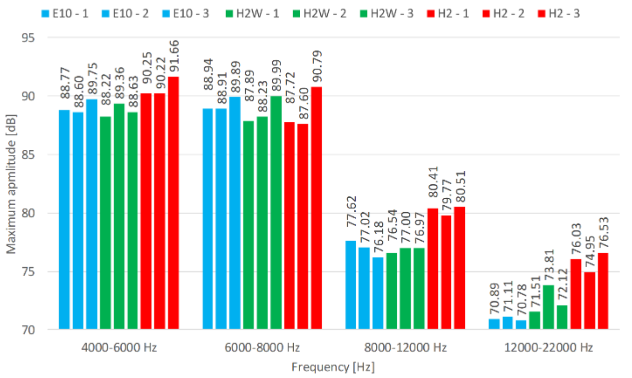

Fig. 8. Maximum noise amplitude values for selected frequency ranges from all tests for three different engine operating conditions

The acoustic noise analysis system also allows localisation of the noise source in the recorded image. For this purpose, the program performs interpolation of the noise amplitude level in the selected frequency range and applies these values to the recorded image. The system has 16 independent microphones, which makes it possible to accurately analyse the location of the noise source. Figure 9 shows the results of such analysis for selected frequency ranges. Unfortunately, the software does not allow the presentation of results averaged from several measurements, so it was decided to present the results from measurement no. 3 for each type of engine fuel supply strategy. Figure 9 also shows the maximum noise values for each sample. Note that the legend of the results was selected individually for each frequency range. As can be seen from the presented results, each noise location corresponds to the location of the Wankel engine body. In addition, the difference in the amplitude level of the noise is visible, which is the same as the previously presented results in the form of waveforms or graphs. It was not decided to present the results in the 12,000–22,000 Hz frequency range graphically due to the lack of visualisation of the focused source of the noise.

4. Conclusions

This article presents the methodology and results of acoustic testing of a rotary piston engine, the Wankel Aixro XR50, fueled with three different fuel strategies: motor gasoline only (E10), hydrogen with water (H_2W), and hydrogen gas only (H_2). The use of an acoustic camera during the study made it possible to analyse in detail the sources of noise and their location for different frequency ranges. Experimental studies showed that the greatest differences in noise emission occurred in the high frequency range (above 8000 Hz), especially when the engine was supplied with pure gaseous hydrogen (H_2).

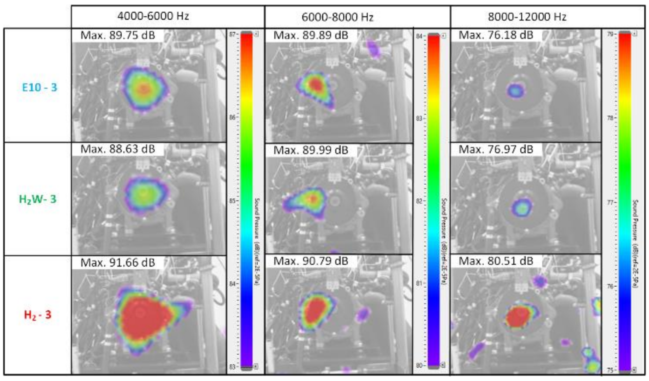

Fig. 9. Noise source localisation for selected frequency ranges for three different engine operating conditions

The supply of hydrogen with the addition of an injected dose of water (H_2W) allowed for the reduction of the intensity of noise, which confirms the effectiveness of supplying water to the combustion chamber in reducing noise, and thus in mitigating contact combustion of the gas-fueled engine. In addition, it can be concluded that water injection in the case of gaseous hydrogen fueling reduces noise intensity levels, particularly evident in the high frequency range (8000–22,000 Hz), and noise source location maps confirm that the dominant source of noise emissions is within the chamber where the heat generation process takes place, regardless of the power supply strategy, but the intensity level is clearly highest for pure hydrogen fuel (H_2). By using an advanced measurement system, it was possible to quickly and precisely identify the source of the noise, which can provide a basis for further optimisation of the design and power strategy of Wankel engines using alternative energy sources, especially hydrogen gas. As part of future research, we plan to conduct a comprehensive analysis of the noise source using Noise Inspector and measure the pressure in the combustion chamber, which will enable precise identification and characterisation of the knocking phenomenon.

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Nomenclature

AE	average energy
ANN	artificial neural network
DWT	discrete wavelet transform
ECU	electronic control unit
EFD	early fault detection
EFI	electronic fuel injection
HD	high definition
HRR	heat release rate based on the knock metric
IMPO	integral of modulus of pressure oscillations
MAPO	maximum amplitude of pressure oscillations
MVTD	minimum value of the third derivative
SI	spark ignition
SIL	speech interference level
WPA	wavelet package analysis

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