Studies in Conservation

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ysic20

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STUDIES IN CONSERVATION
https://doi.org/10.1080/00393630.2023.2183808

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Acoustic Emission Monitoring as a Non-invasive Tool to Assist the Conservator in the Reactivation and Maintenance of Historical Vehicle Engines

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ABSTRACT
Historical cars are an important part of the cultural heritage of the last 150 years. Their preservation in technical museums raises the question of how to preserve their primary functionality, namely their mobility. This implies being able to reactivate and to maintain their thermal engines, which are the source of their motion. However, the diversity and complexity of these engines generally require the presence of highly qualified personnel as well as detailed condition reports to assist the conservators. This study proposes to use acoustic emission techniques to facilitate these conservation procedures by objectifying the evaluation of the state of the engines and by providing systematic quantitative indicators for their health monitoring. To illustrate the implementation and the potentialities of this approach, different tests have been carried out at the National Automobile Museum of Mulhouse, on a Renault Type AG1. A dedicated experimental setup and the associated measurement protocol are presented in this paper. The derived results show the ability of this method to detect specific types of engine malfunctions, both during bench test and *in situ* measurement conditions. A critical discussion is finally proposed to highlight the feasibility and the possibilities of such laboratory techniques in the context of conservation assistance.

ARTICLE HISTORY
Received December 2021
Accepted February 2023

KEYWORDS
Industrial heritage; historical car; non-invasive maintenance; internal combustion engine; acoustic emission

Introduction

Conservation of historical vehicles

The presence of mechanisms and moving parts is typical of specific categories of cultural heritage artifacts that can be found in technical, industrial, and scientific collections. Their movement and therefore their functionality is an integral part of this type of heritage. This means that they should be kept in conditions allowing their operation when necessary, or else part of their cultural value is lost. In the context of technical museums, their conservation should therefore take into account not only their visual aspect but also other sensations that can be transmitted to visitors only through movement (including sound). Indeed, as emphasized by Wagensberg, the aim of museology is to transmit a tangible reality to the visitor (Wagensberg 2010). These statements particularly stand for historical vehicles, which are synonymous with mobility, speed, or even purring engines in the collective unconscious.

Preserving historical cars in their original condition is the primary mission of the Musée National de l'Automobile – Collection Schlumpf (MNAM) in Mulhouse, France, for heritage, didactic, and sociological purposes. This collection consists of 600 cars, ranging from early models to contemporary ones. The meaning attributed to this notion of 'original condition' (e.g. straight from the factory, in its actual state of wear, focused on its active functionality), highly impacts the implemented conservation and renovation processes (Rapetti 2017). For a long time, the conservation of functional objects was based on traditional treatments, unrelated to the history of these objects, leading to a loss of their cultural and historical characters. However, since the 1990s, a general consensus seems to be emerging, both in museums and among private collectors, privileging the interest of a careful maintenance instead of a restoration which could denature the object (Ashton and Hallam 1990). Moreover, the functional aspect directly raises the question of static versus dynamic conservation (ABTEM 2018). In the former case, the original function of the vehicle is largely lost, and the emphasis is put on the external aspect of the object. In the latter one, the vehicle is used

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(or at least activated) periodically, implying regular maintenance operations. This emphasis on the functionality may possibly lead to modification, therefore altering the originality of the vehicle (Newey 2000).

Although such conservation issues are likely to concern more and more museums because of the inclusion of technical objects in many collections, only a few scientific studies have been published on this subject. The main contributions often come from specialized or grey literature (Simeone 2012; Charter of Turin Handbook 2017) and exchanges between museums and collectors. As an example, the National Museum of Australia has developed conservation techniques to preserve the significance of the exposed objects, leading to the dynamic conservation of the Francis Birtles Bean car, under operational running conditions (Brunott et al. 2010). However, there are still divergences about the notion of original state and the impact that maintenance or restoration actions can have (Collum 2012; Keller 2020).

For the last ten years, the MNAM has decided to keep 80 cars in a fully functional state, by restoring and maintaining their engines. Since those mechanisms are typically composed of a large number of different parts and subsystems involved in their operation, their reactivation is not an easy task for a conservator and requires specific competences and knowledge, including technical skills and a mechanical background. The reactivation becomes even more challenging if their functioning were stopped for a long period, because the presence of corrosion products, deposits, oxidation, particles, and the scaling of oils or lubricants can greatly influence the movement. The presence of these extraneous products can prevent the mechanisms from operating properly or even lead to their breakdown just at start-up. Hence, in addition to the expertise of the conservators, detailed and systematic monitoring procedures are necessary to allow a safe operation of these historical cars while respecting their authenticity, i.e. trying to preserve as much as possible the original components of the mechanisms.

Reactivation of old car engines

To the authors' knowledge there is no standard procedure dedicated to the reactivation of old car engines. However, such procedures should be rigorous and technically supported as the operational use of this historical heritage should not be at the expense of its long-term conservation and transmission. To tackle the deriving issues, the automotive conservation-restoration field has developed different approaches over many years. These have been investigated through a survey conducted on 43 institutions, museums (e.g. national technical ones, automotive brand ones), and private collections around the world. Of these, 23 agreed to answer an online form consisting of ten questions, in both open and closed format (Chalançon 2019).

In 10% of cases the engines are reactivated without any diagnostics. The correlated risk makes it hard to perform and requires both extensive documentation and personnel with in-depth knowledge of the considered engine. In 35% of cases, the engines are removed and fully dismantled beforehand. While enriching the technical knowledge on the engine itself, it still requires high mechanical skills (disassembly/reassembly, metrology) and implies important costs and intervention times. Finally, in 55% of cases, preliminary controls are performed, without complete dismantling.

This third approach has also been implemented at the MNAM. The first step usually consists in studying the available documents and determining a list of the controls to be performed, according to the specification of each engine. Then, visual inspections are carried out by naked eye or using an endoscope to check, for example, the integrity and the state of internal surfaces like cylinders. The engine shaft is further gently moved by hand to listen for any noise that might indicate a possible malfunction, and the valve train system is more specifically checked. If all the results of these tests are validated, the engine may eventually be restarted. While offering a compromise between the previous approaches, it still requires a high level of expertise and is largely based on subjective judgement. Hence, introducing physical measurement techniques could allow conservators to objectify and to sustain the diagnosis and monitoring of old car engines.

Non-invasive maintenance techniques

Vibrations and acoustics have always been key features in diagnosing the condition of an engine, as illustrated by the 'noise listener' professional figure found in mechanical workshops until the middle of the twentieth century (Lambert 1976). Dedicated *in situ* measurement techniques are now widely implemented into modern cars to detect particular issues: for example, piezoelectric sensors for detecting rattling noises which allow adaptation of the ignition point of the engine to avoid any premature wear. In parallel, vibration analysis methods have been developed over the last 20 years in the industrial research field on structure health monitoring, as non-invasive approaches to evaluate gear or bearing wear phenomena (Antoni and Sidahmed 2004; Migeon 2011). They have proven to be particularly effective in detecting structural defaults but require significant technical resources and the ability to perform measurements in a controlled environment.

Acoustic emission (AE) testing uses piezoelectric sensors, mounted on the surface of a material or a structure to measure elastic waves (i.e. solid deformations traveling through the structure without causing permanent physical changes) at frequencies usually ranging from 100 Hz to 1 MHz (covering both audible and ultrasonic spectra). Mechanical deformation and fracture are the main sources of AE. The AE must be initiated by subjecting the tested structure to a stress-inducing event such as an impact and are then detected by the piezoelectric sensors. AE measurements have been proposed as a non-destructive technique to monitor the multiple phenomena deriving from the propagation of transient elastic waves from defects inside materials (e.g. structural deformations, crack propagations, impacts) (Roget 1990). Their high frequency content enables detection of signals both within the range of human hearing and in the ultrasonic spectrum. Most applications are related to various industrial issues (Bellenger et al. 2002; Wu et al. 2015; Martin del Campo et al. 2019). For example, AE is widely used for detection of cracks (Keshtgar and Modarres 2013), even at early stage in different materials (Goszczyńska et al. 2012), including rotating gearbox components (Xiang 2017). Recent research has focused on car engines. Kaul et al. were able to precisely observe characteristic events associated with the engine cycle, such as valve closing or fuel injection (Kaul, Lawler, and Zahdeh 2016). Shuster et al. showed the use of AE to identify the onset of piston wear (Shuster et al. 2000). Delvecchio et al. proposed a critical review concerning the monitoring of internal combustion engines, including AE approaches, emphasizing their ability to detect spark plug or injector malfunctions (Delvecchio, Bonfiglio, and Pompoli 2018). While AE seems particularly adapted to the non-invasive auscultation of various objects, it has until now been rarely used in the conservation field, even if a very recent publication promoting this technique recommends greater use (Łukomski et al. 2020). Among the few studies applying AE to cultural heritage, one example is the work of Le Conte et al., who were able to diagnose xylophagous insects in historical wooden musical instruments (Le Conte et al. 2015).

The aim of this study, developed in the framework of the ACUME_HV project (Brambilla et al. 2021), is therefore to propose a method to be added to a museum's maintenance protocol to help the conservators to diagnose possible degradations present on historical car engines, using acoustic emission sensors, in order to secure their reactivation process. The aim is, obviously, not to replace the necessary condition report and initial examination, but to support the expertise of the museum personnel with numerical data that can be compared at different time periods to follow the possible engine's condition evolution. This method could also be further used as an engine health monitoring tool to guarantee integrity throughout use in a dynamic exhibition context.

The remainder of the paper is organized as follows. The next section introduces the historical car from the MNAM collection that was used to develop and test the proposed method. A brief description of the technical functioning of a thermal car engine is also given. Then the materials and method section presents the general principle of acoustic emission and describes the associated experimental materials. The preliminary tests and the measured features are also precisely detailed. Following that, typical results are presented, and the potential of this method is illustrated by fault simulation tests and *in situ* measurements. Then a critical discussion section underlines the concrete feasibility of the proposed approach for the museal institution, its main limitations, and some possible evolutions. Finally, concluding remarks are given.

The Renault AG1 engine

Historical context

For the past ten years, the MNAM has decided to maintain about 80 vehicles in running condition in order to offer a valuable experience to visitors but also to preserve the knowledge and know-how associated with such historical objects. Among these, the Renault Type AG1, illustrated in Figure 1 (left), was chosen for this study.

Built in 1909, it is better known under the name 'Taxi de la Marne', as it was equipped with a landaulet body and used as a taxi in Paris before World War I (Keller and Garnier 2014). It was bought in 1961 by Fritz Schlumpf (founder of the car collection with his brother Hans Schlumpf) from a previous owner who had had it refitted. Its main advantage is an easily accessible engine, simple to operate and with only two cylinders. It was completely serviced in 2000: the car was dismantled and all subcomponents were checked and restored when necessary. Since then, the car is driven about 50 km per year, either on the racetrack of the MNAM or during events throughout Europe. In addition, the MNAM owns a spare copy of this engine (further referred to as the 'bench engine'), without patrimonial status, allowing to setup the tests without any risk, as illustrated in Figure 1 (right).

Technical description

This engine is a traditional four-stroke internal combustion one, as described in Figure 2, with a 1205 cc displacement, developing 8 hp at 1500 rpm. Its operation can be described as follows. During the intake, the air–fuel mixture enters the cylinder through the

Figure 1. Renault Type AG1 in the exhibition hall (left) and spare engine (right) in the reserve collection of the museum.

intake valve; this mixture is then compressed inside the cylinder; an electric spark created by the spark plug ignites the mixture and creates an explosion that pushes the piston back; the spent air–fuel mixture is expelled through the exhaust valve. Each of its pistons, phased at 180°, must pass these strokes to achieve one thermodynamic cycle, thus corresponding to two motor shaft revolutions, namely 720°.

Materials and method

Acoustic emission (AE) technique

Within the framework of this study, the idea is to measure, at the surface of the engine, the AE signals related to the motions of its multiple sub-components while running through the different strokes of a cycle. These relative motions introduce friction between components due to their surface condition and small impacts at loose connections, all acting as emission sources and generating transient elastic waves. These

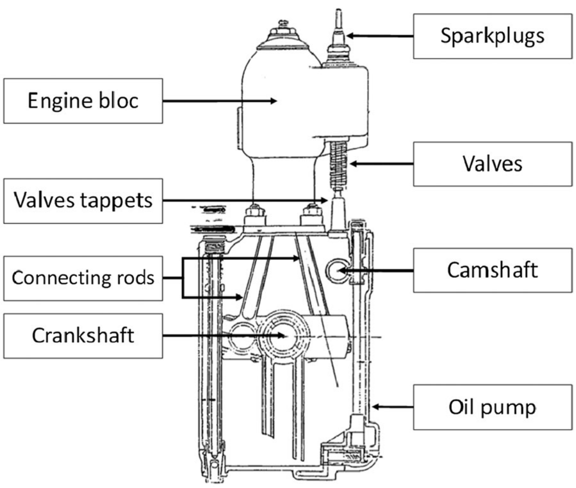

Figure 2. Schematic of the four-stroke engine [Renault 1911].

initial waves then travel through the different solid media creating secondary sets of transient elastic waves by diffraction, at each interface or discontinuity. A single stress source inside the engine can therefore generate a burst of elastic waves, resulting in multiple displacement hits recorded by each sensor mounted on its external surface.

An AE system from Vallen (MB2-V1) was used to acquire the AE signals measured by four broadband piezoelectric AE sensors (VS900-M, between 100 and 900 kHz) and their preamplifiers (AEP5, + 34 dB). A low pass filter of 1 MHz was applied before acquiring the AE signals at 2 MHz sampling frequency. The crankshaft angular position was also measured with a full continuous 360° smart position sensor VISHAY Spectrol 601–1045 (output signal 0-5 V) at 125 kHz rate. The obtained data were recorded using Vallen AE-Suite software (Vallen 2017), allowing further post-processing.

A dedicated arm was designed to properly mount the sensor on the engine. As prescribed by the manufacturer, a minimum 10N force must be applied to the sensor to ensure a constant contact pressure throughout the test (Vallen 2017). As the surface of the engine is not perfectly smooth, a coupling agent must be used to achieve better surface contact and provide the best high-frequency transmissibility. However, given the conservation prerogative, it is essential to ensure the integrity of the engine surface by avoiding any chemical reaction. Several gels, greases, and waxes were tested in a dedicated survey (Cornet et al. 2020). When working with historical artifacts, even of industrial origin, the non-invasivity of the analytical procedures is of utmost importance. Therefore, the tests of gels and greases had two different aims: on one side to allow a proper transmission of the AE signal and on the other side to verify that no traces were left on the surfaces of the engines, both metallic and painted. Most of the gels commonly used in industry for AE applications left unesthetic white traces on the painted parts of the engines, even after careful rinsing with water and/or ethanol. Waxes were not useful because their removal requires solvents or excessive rubbing that can damage the painted surfaces. Moreover, the transmission of the signals was attenuated. The greases gave quite good results for both the searched aspects. The Miocar grease was finally selected as it does not leave any trace on the application area. This grease is used in the field of historical vehicles conservation; it left no traces on painted and bare metal parts of the engine and showed performances in terms of signal transmission of acceptable quality.

Preliminary tests

As a precaution, preliminary tests were performed on the bench engine, mounted on a dedicated test bench, allowing simple access to its different parts while keeping all cam system and pump mechanisms operative. It was manually operated with a handle on the crankshaft, at a speed low enough to avoid any damage while maintaining AE signal levels high enough to be characterized.

A first set of tests was then performed to identify optimal locations for each of the four sensors (Brambilla et al. 2019; Chalançon 2019). It must be noticed that the test bench offered ideal accessibility to the various surfaces of the engine, allowing us to consider various sensor configurations. However, such a systematic approach may be hard to implement for most historical engines due to the very limited space available around them. In the most complicated cases, it could be necessary to develop alternative sensor mounting systems to gain access to the targeted parts of the engine.

Areas close to sensitive components or interfaces between them were tested, looking for distinctive and repeatable AE signals, with high response levels and a good signal-to-noise ratio. Figure 3 shows the final location of the sensors: on the cylinder block close to the first cylinder (n°1) and to the cylinders' valves (n°2); on the crankcase, on the cover of the gear of the cam system (n°3) and on the leg (n°4) (Roda-Buch et al. 2019).

A second set of tests was conducted to analyze the effect of the engine rotation speed on the AE signal level (Brambilla et al. 2019; Chalançon 2019). Different tests were performed by manually varying the speed between 0.25 and 1.2 cycles per second (cps). In order to avoid air compression inside the cylinders, the spark plugs were momentarily removed. This resulted in smoother engine movements. Finally, a third series of tests was performed with the spark plugs back on, to better observe the in-cylinder air compression and its impact on the AE signals.

Post processing of typical AE signals

The feature used to characterize the recorded raw AE signals is the root mean square (RMS) level of the measured surface displacements, as it is related to the energy of the physical phenomena generating these underlying AE signals [e.g. sliding friction processes in contact pairs (Nivesrangsan et al. 2007)].

Figure 4 illustrates the AE RMS level measured at sensor n°1 during a preliminary test, without spark plugs. Each dot corresponds to the amplitude of a single burst and the line represents the associated moving average, in order to smooth the overall behavior. It can be observed that there is a high correlation between the AE RMS level and the crankshaft angular position and, consequently, the relative motion of the position within the previously described thermodynamic cycle (i.e. two full crankshaft rotations, or 720°).

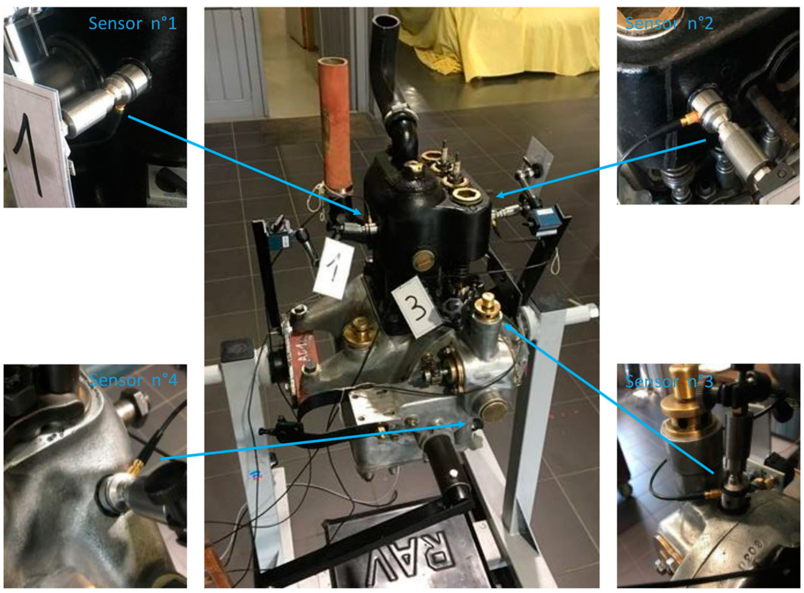

Figure 3. Optimal locations of the sensors on the spare engine [Chalançon 2019].

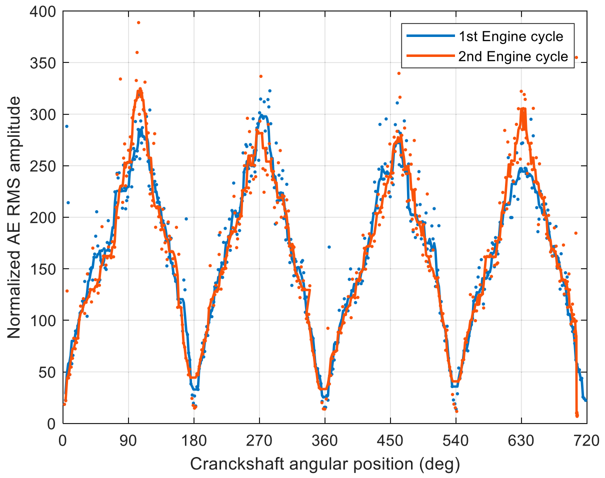

Figure 4. Preliminary test measurement at sensor n°1 (without spark plugs).

Indeed, the angular position sensor was calibrated so that it assumes 0°, 360°, or 720°, when the first piston is at its top dead center position (TDC) and the second one at its bottom dead center (BDC) (and conversely at 180° and 540°). The minimum values of the AE RMS occur at these positions (i.e. TDC and BDC), where the speed direction of the piston changes, while maximum values occur at mid positions where the piston speeds are maximal. This indicates that the main source of AE signals comes from the sliding friction between the piston rings and the cylinder liners. Such signal patterns associated to the unmounted spark plug configuration can thus be considered as a purely mechanical signature, characterizing a unique engine.

As detailed in a previous publication (Roda-Buch et al. 2021), signal amplitude issues related to variations of the crankshaft rotational speed were highlighted. These were due to the manual rotation and the variable resistance torque of the engine during its motion. However, this manual operation is very important to preserve the condition of the engine. It allows one to control the rotation speed and to stop the test at any time. Moreover, when testing an engine for the first time, it also allows one to be attentive to the slightest noise or abnormal sign or resistance of the moving parts. To allow comparing AE RMS levels at different angular positions along the same test and between different tests, a normalization of the AE RMS level to an average 0.5 cps was proposed.

As observed in Figure 5, this normalization does not modify the shape of the signals, thus preserving all the characteristic events of the measurement. Peaks are located at the same angular position, whatever the engine cycle, on both raw and normalized signals. However, the post-processed signals show identical signal amplitudes, whatever the engine cycle. Thus, this normalization ensures the repeatability of the measurements.

Results

Analysis of the bench engine

Figure 6 shows the AE RMS levels measured on the bench engine, following a complete condition report and careful mechanical adjustments. The tests were performed with the spark plugs on, but still without any fluid in both cooling and lubrication systems. This configuration can thus be considered as reflecting a nominal operation mode, without any failure, under ideal conditions.

It can be observed that the four back and forth reciprocating motions of the pistons are less discernable. However, sensors n°1 and n°2 exhibit the same evolution with regard to the rotation angle. They may thus reflect the same physical phenomena whose sources seem to be located near the pistons and cylinders, with the amplitude difference being related to the distance to the sensors. The clear increase of the AE RMS level in Figure 6(a) around 90-180° and 630-720° can be associated to the compression phases in the second and first cylinder, respectively. This indicates the absence of leaks in the cylinders and therefore the good condition of the valves and rings, which are parts surrounding the pistons. Punctual spiky events at 170° and 350 ° are also noticeable, reflecting the valve opening and closing operations. Hence, these AE patterns can be interpreted as the combined mechanical and airflow signature of the engine.

Fault simulation tests

Following these reference tests, fault simulations were conducted to evaluate the ability of the AE monitoring approach to detect classic mechanical failures, such as gaps between the connecting rod and the crankshaft or between the piston and the crankshaft (Brambilla et al. 2021). These were chosen as they correspond to classic faults that prevent the proper operation of an engine. By introducing these faults, additional noisy events are expected to occur on the AE signal at localized angular positions, especially at mid-stroke or when pistons change direction.

To simulate the gaps between the connecting rod and the crankshaft, 1 mm-thick shims were added between the connecting rod and the connecting rod cap. As illustrated in Figure 7, perturbed AE RMS signals with slightly higher mean levels can be observed at sensors n°3 and n°4, which are located near the cam system, suggesting the presence of new AE sources. This clearly reflects the expected malfunction which should generate noise around mid-stroke (e.g. around 90° and 270°). Due to the distance between the sensors and the piston, the previously described four-part pattern associated to the piston

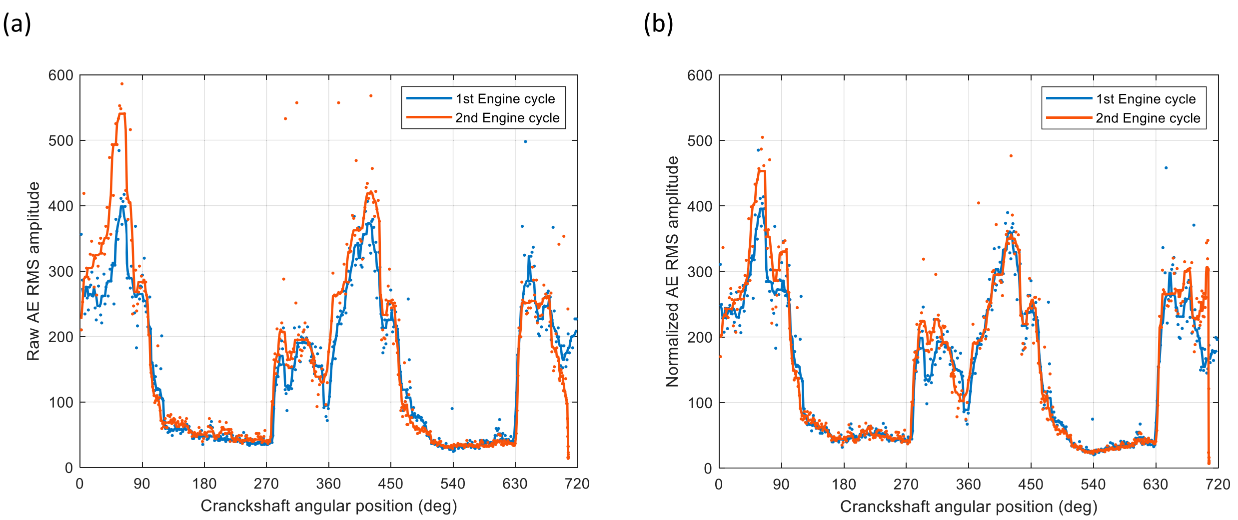

Figure 5. AE signal amplitude with the crankshaft angular position, before (a) and after (b) its normalization.

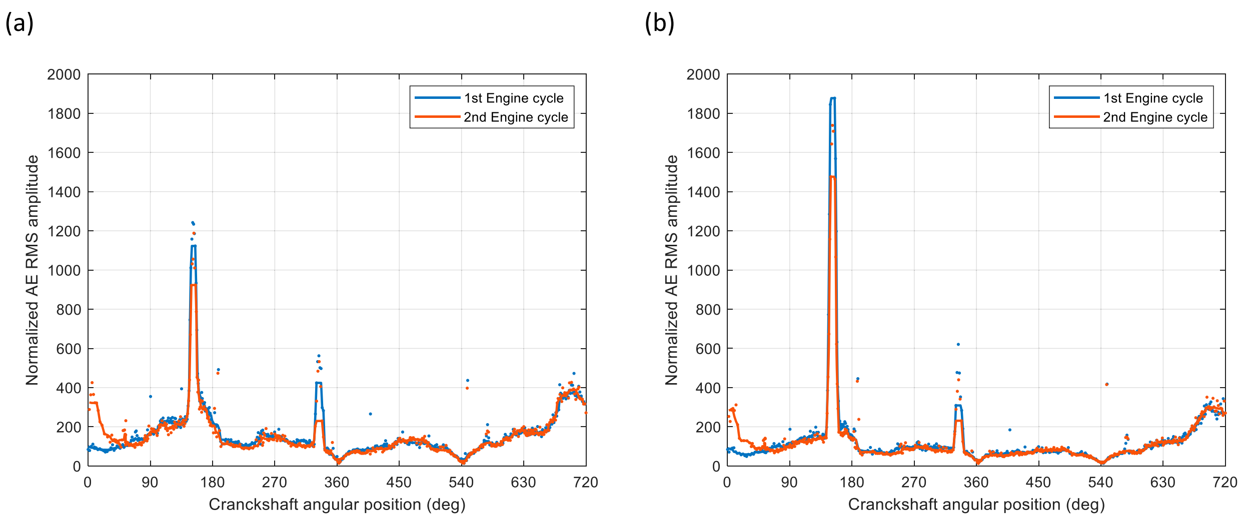

Figure 6. Reference test measurement with spark plugs, sensor n°1 (a) and n°2 (b).

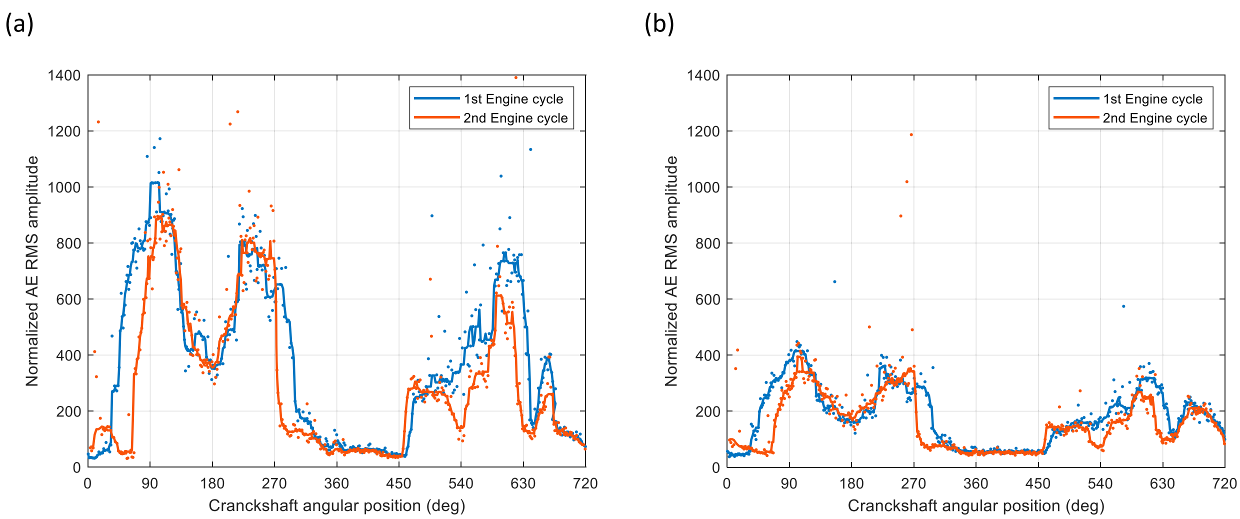

Figure 7. Fault simulation test – gap between connecting rod and crankshaft, sensor n°3 (a) and n°4 (b).

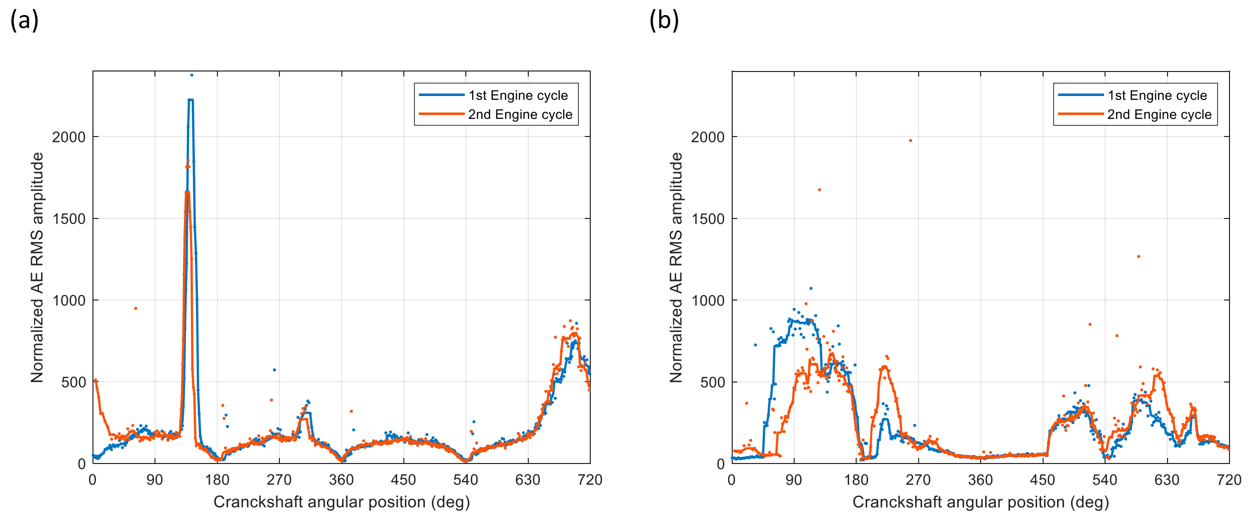

Figure 8. Fault simulation test – gap between piston and crankshaft, sensor n°2 (a) and n°3 (b).

stroke is less noticeable and maximum amplitudes seem to occur at mid-stroke. To simulate the latter, a piston pin with a smaller diameter than the original one has been machined and installed to generate the gap. Figure 8(a) clearly shows a doubled AE RMS level at 720°, at sensor n°2, during the compression of the first piston. This may result from a series of small shocks during this phase of the cycle, also generating a higher mean level at sensor n°3.

Hence, if a faulty engine operation does modify its acoustic signature, it remains difficult to interpret. Although a defective operation mode can be detected from the variations of the AE signal amplitude, this feature does not seem sufficient to characterize the nature of the underlying physical phenomena.

In situ *diagnostic of the historical engine*

Finally, the proposed AE process was applied to the historical engine of the Renault Type AG1, as part of its maintenance monitoring (Chalançon 2019). In accordance with the conservation strategy implemented at the MNAM (as described in the section *Reactivation of old car engine*), a global condition report of the car without a complete dismantling of the engine was carried out, confirming a very good external condition, as already documented in the maintenance report of the MNAM. It was followed by an endoscopic inspection of the cylinders, showing some combustion residues but no mechanical degradation. The idea was therefore to carry out some 'blind' acoustic emission measurements to confirm or contradict this partial condition report (i.e. without any detailed verification of its interior).

As illustrated in Figure 9, the AE sensors were mounted on the engine, as close as possible to their optimal location (described in the section *Preliminary tests*), despite the access difficulties due to the attachment of the engine on the chassis. The angular position sensor was directly mounted on the magneto shaft and preliminary measurements were performed to determine the engine distribution diagram, which differs from the bench engine one, due to varying camshaft assemblies. Indeed, as the geometry of the cams may slightly vary from one engine to another, the relative motions of the valves may also be slightly modified, thus shifting the characteristic position of the engine cycle up to 30°. Moreover, as indicated in the section *Preliminary tests*, particular attention was paid to avoiding any esthetic damage during the test set-up.

The AE measurements were further performed with mounted spark plugs and fluids on both cooling and lubrication systems (i.e. under normal operating conditions), by manually rotating the crankshaft to approximately 0.5 cps. Such 'cold-test' procedure does not require restarting the engine, thus allowing minimizing possible damages.

As observed in Figure 10, the derived AE signal levels are quite similar to the bench engine ones (*cf.* Figure 6) but slightly noisier. A closer look reveals that, while the compression of the first cylinder can be observed around 700°, the compression of the second one does not appear around 180°, as normally expected. This AE signal feature could indicate a sealing issue of the second cylinder, as explained in the section *Fault simulation tests*. However, no such malfunction was noted during previous maintenance nor during the preliminary condition report. A specific sealing test was thus carried out on the second cylinder, highlighting a fault in the seat of the intake valve, leading to an approximate 35% loss in compression (Chalançon 2019; Roda-Buch et al. 2021).

If this failure had not been detected in time, it could have created instabilities in the engine during operation, leading to unbalanced vibrations. In the long term, these could damage the contact surfaces

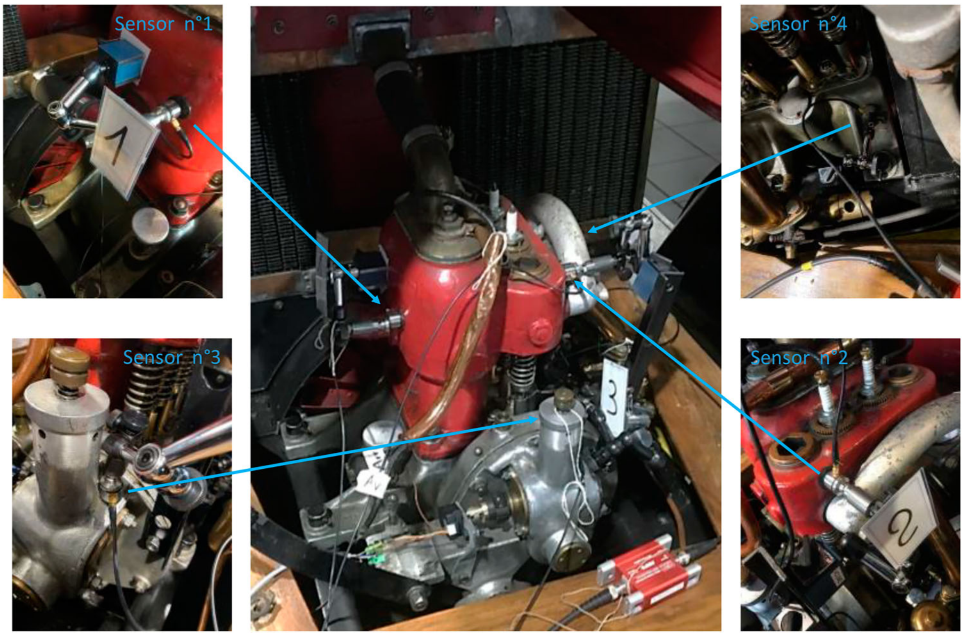

Figure 9. Locations of the sensors on the historical engine [Chalançon 2019].

between the different internal parts of the engine, resulting in premature wear or even a complete engine failure. While a manometer can be typically used to measure the pressure leakage, it assumes that dedicated tests have been previously performed to diagnose such failures. On the contrary, the proposed AE monitoring procedure allows identifying, evaluating, and monitoring such failures directly from generic measurements of acoustic signals. In the specific case of this Renault Type AG1 historical engine, it allowed anticipating possible degradations and scheduling preventive conservation actions.

Discussion

As shown in this study, acoustic emission is a non-invasive way to make accurate and repeatable measurements to characterize the cold operation of an historical engine. If the results obtained and detailed above offer a first approach towards the diagnosis of the engine health monitoring, they are currently closer to research laboratory work than to an engine reactivation protocol. The development and the generalization of this approach within the framework of conservation thus raises a certain number of questions.

Although acoustic emission has become more and more used in the industrial domain, especially for the health monitoring of mechanical structures, the cost for a complete acquisition system (between 20k€ and 40k€) remains a heavy investment for most museum institutions. It is also necessary to include training costs for the personnel who will use it, as they are often not specialized in this technical field. During this study, the collaboration with a research laboratory

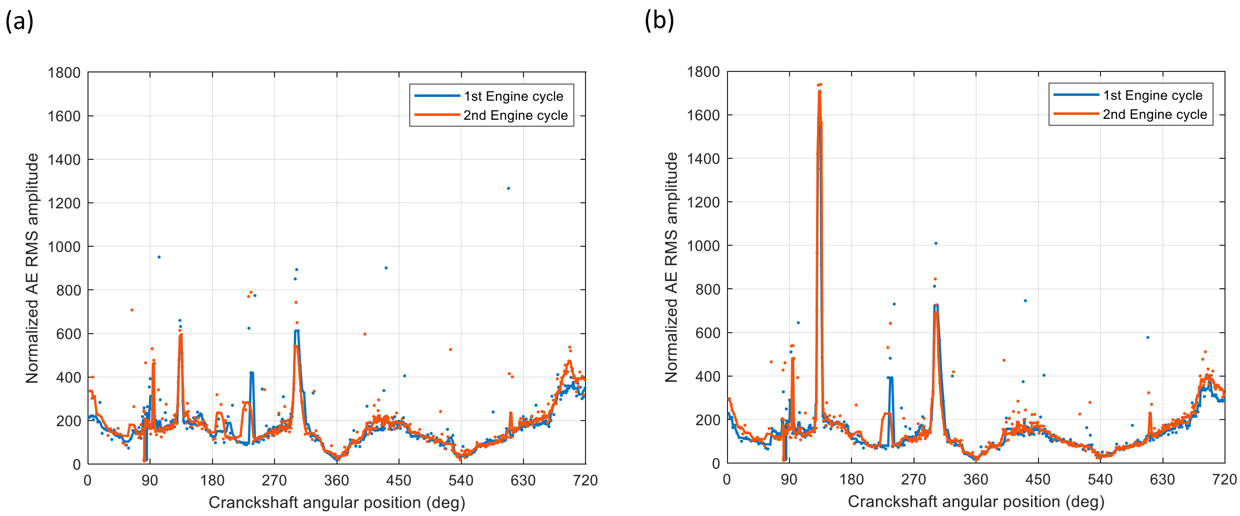

Figure 10. *In situ* historical engine test, sensor n°1 (a) and n°2 (b).

and an engineering school enabled rapid handling of the experimental results. Moreover, the complementarity between the conservator's in-depth knowledge of the engine and the scientific approach of the research team, based on the understanding of the measured signals, made it possible to quickly determine the experimental protocol as well as the best adapted post-processing procedures. In return, it allows scientists to study specific objects and unique databases, to which they do not usually have direct access, and to eventually apply innovative processing techniques (e.g. advanced signal processing, statistical approaches, machine learning techniques).

Hence, condition assessment procedures prior to the reactivation of historic engines could be partly accelerated and objectified by using acoustic emission measurements. This would be all the more interesting in the context of maintenance over time: a characterization at an initial moment, following a detailed condition report (e.g. based on a total dismantling of the engine), could thus be compared with complementary measurements, at regular intervals. The relative evolution of the acoustic emission signals could then be used as an indicator to anticipate any future important degradation.

From a more technical point of view, the so called 'cold-tests' could be completed by 'hot-tests'. The former permit recording of the mechanical signature of the engine, under very controlled conditions, independently from parameters such as quality and effect of the temperature on lubricants and fuel and, most important for historical vehicles, almost no risk for the engine. On the other hand, the latter are performed with the engine started and running, also allowing recording of the combustion signature. While such tests could supply more complete data about the engine, and the possibility of detecting some malfunctions which are not visible with cold-tests, some mechanical issues might also be masked by the combustion noise. Moreover, hot-tests are riskier as they load the engine at higher and more demanding speeds, which may be inappropriate for a safe reactivation.

Finally, such a maintenance procedure could be further developed at the MNAM, where each car of the collection is restarted once a year. As the procedure stands, three to five days of handling would be necessary for a single engine, but this time could be reduced by the various forms of feedback. All these measurements could be gathered in a database, making it possible to seek identical behaviors among all the engines, thus partly mitigating the important heterogeneity in the design of the engines.

Conclusion

An original approach based on acoustic emission techniques has been proposed in this study, to help reactivate historical car engines. It essentially allows deriving objective diagnostic features corresponding to the mechanical signature of the engine condition, from non-invasive 'cold-test' measurements. This method should not replace the necessary initial examination and condition report prior to reactivation, but should be used to support the expertise of the museum personnel with numerical measurements. The complete description of the equipment used, and the preliminary tests carried out, makes it possible to outline a general measurement protocol which could be extended to other types of engines. A dedicated post-processing of the measured AE signals has been implemented to normalize their RMS levels with regard to the crankshaft rotation speed, measured using a dedicated sensor, providing repeatable features. Their ability to characterize the different phases of the engine thermodynamic cycle as well as some 'classical' malfunctions (e.g. piston sealing issues) has been illustrated on a Renault Type AG1 engine, under both bench-test and *in situ* conditions.

In the context of dynamic conservation of historical vehicles, this technique can be included in the maintenance monitoring of their engines. Hence, following a thorough diagnostic, reactivation, and renovation phase, a proper initial AE signature of each engine could be recorded, stored, and further compared to subsequent measurements. This could allow tracing possible evolution of an engine's state and therefore it could then be used as a diagnostic tool to help in anticipating and scheduling conservation actions.

Acknowledgements

The authors would like to thank Jean-Charles Peruchetti, associate professor at the Université de Haute-Alsace, for his support and his valuable assistance in setting up the angular measurement system.

Disclosure statement

No potential conflict of interest was reported by the author (s).

Funding

This study has been supported through the ACUME_HV Project, funded by HES-SO RCDAV, Switzerland.

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