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Diagnostic of historical vehicle's engines by acoustic emission techniques

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***Abstract* – The reactivation of artefacts' mechanisms is always a challenge for conservators and proper non-invasive diagnostic techniques, applicable directly on the artifacts, allows to perform a precocious diagnostic and to avoid damages. The ACUME_HV project (Acoustic Emission Monitoring of Historical Vehicles) represents the first use of acoustic emission (AE) as non-invasive technique for the diagnostic of historical vehicles. The aim of this project is to propose an objective, human-independent method that will help the personnel of the museums to take decisions concerning the reactivation of the historical vehicles' engines using measurements and data and not only personal experience. In this paper the results of the first phase of the ACUME_HV project are presented. This first phase focused on the development of a protocol for the use of AE during cold tests.**

I. INTRODUCTION

The peculiarity of the objects constituting the technical, industrial and scientific cultural heritage is the presence of mechanisms. The functionality of these objects, i.e. the possibility to make them work, is an integral part of the object itself. The reactivation of these mechanisms, however, is often a challenge for the conservators, in particular if the functioning was stopped for a long period. In fact, the presence of corrosion products, deposits, oxidation, particles and the scaling of oils or lubricants can prevent the mechanisms from working properly or even lead to their breakdown in case of reactivation. In addition, this procedure should be performed respecting the material authenticity of the object, i.e. trying to preserve as much as possible the original components of the mechanism.

Among the objects with mechanisms, vehicles are particularly complex, because of the number of parts and or sub-systems involved in their functions. Given the difficulties previously mentioned for the reactivation of engines, the choices of exhibition and maintenance of historical vehicles in museums and collections are usually only two:

- static: the vehicle is exposed and its engine is never operated or sometimes the engine is even removed from the vehicle for practical and safety reasons.
- dynamic: the vehicle is used or at least activated periodically.

In order to be able to reactivate the mechanisms without damages and, at the same time, preserve the cultural values and the materials originality of the objects, the conservators need diagnostic tools for the detection of malfunctions at the very early stages.

In the field of historical vehicles conservation, there are not, at present time, reliable non-invasive techniques for the diagnostic and monitoring of the engine's functioning. Therefore, the maintenance of old engines requires personnel with specialized competences and it is particularly time consuming. The evaluation of the correct functioning is left to the expertise of the specialists and they base their evaluation mainly on their previous experience from a visual examination and the listening of the noise of the engine. This method is empirical, human-dependent and cannot be correctly standardized.

In this respect, the use of non-invasive techniques, such as Acoustic Emission (AE) for the evaluation of the mechanisms' condition [1, 2] may help to avoid damages during the reactivation and to develop a monitoring protocol based on factual measurements.

The ACUME_HV project (Acoustic Emission Monitoring of Historical Vehicles), led by HE-Arc CR, represents the first use of acoustic emission (AE) as non-invasive technique for the diagnostic of historical vehicles. The aim of this project is to propose an objective, human-independent method that will help the personnel of the museums to take decisions concerning the reactivation of the historical vehicles' engines using measurements and data and not only personal experience.

II. METHODOLOGY

A reliable diagnostic tool must be able to capture signal features that can be correlated to the state of the system. The Conservation-Restoration procedure to reactivate an engine starts with a visual inspection of the whole engine in order to evaluate its individual components' general condition. At this stage, oil and cooling system liquids are changed and accessorial components are repaired, if necessary. The next step, before starting the engine, is to state the functioning of the mechanisms. In order to do this, the engine is moved by hand and an expert verifies the engine operation, visually and acoustically. This procedure is called "cold test" and it is performed without starting the engine, in order to minimize possible damages. The combustion process is therefore excluded from this evaluation and only the mechanical processes are taken into account. At this critical stage, the procedure developed during the ACUME_HV project includes the measurement of the AE signals generated by friction at different contact pairs, such as crankshaft/ connecting-rod/piston, piston-rings/cylinder-skirt, or cam system chain. The airflow or air leakage at valve inlets/outlets and between piston-ring/cylinder-liner gaps are also evaluated. The following step is to obtain the mechanical signature of the engine for different reactivating conditions (i.e. with/without cylinder compression). Finally, specific features are extracted using statistical analysis techniques that can help in classifying the operational state of the mechanical parts of the engine.

III. SYSTEM AND TESTS CONFIGURATION

The AE tests are currently performed on three Renault engines type AG1, belonging to the collection of the Musée National de l'Automobile de Mulhouse (MNAM), France. This type of engine has two cylinders that can develop up to 8 HP.

Firstly, the method was tested on an engine disassembled from the vehicle, in order to have complete access to all the parts of the engine itself. This engine was bought by the MNAM as spare part for possible reparation of the AG1 vehicles. The engine was mounted in a test bench, keeping all cam system and pump mechanisms operative. The mechanism is manually operated at a relatively low rotating speed, through the crankshaft by a handle. This condition allows keeping sensitivity during engine motion, avoiding possible damage to the machine.

An AE system from Vallen® is used to acquire the AE signals. Four AE signals are registered with a MB2-V1 chassis from four broadband AE sensors VS900-M (between 100 and 900 kHz) and their preamplifiers AEP5 (+34dB). A low pass filter of 1 MHz is applied before acquiring the AE signals at 2 MHz sampling frequency. The crankshaft angular position is also measured with a full continuous 360° smart position sensor VISHAY Spectrol 601-1045 (output signal 0-5 V) at 125 kHz rate.

Fig. 1. Renault AG1 (Inv.2209)
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An initial set of tests was performed to evaluate the optimal location of the AE sensors to obtain representative signals from different AE sources. The locations selected for the following tests are those presenting higher levels, lower signal-to-noise ratio, and bigger presence of events for the measured AE signals. Fig. 2 shows the final locations of the four AE sensors, two of them placed on the cylinder block (close to the first cylinder -1- and to cylinders' valves -2-) and another two placed on the crankcase (one on the cover of the gears of the cam system -3- and other on a crankcase leg -4-).

A second set of tests was conducted to analyse the effect of the engine speed on the AE signal level. In this set the spark plugs were removed (avoiding air compression inside the cylinders) to produce a smoother motion of the engine. The engine was driven manually from 0.25 up to 1.2 cycles per second (cps).

A third set of tests was performed to observe the influence of the compression of the air inside the cylinders on the AE signals. In this case the spark plugs where mounted in the engine. The results with spark plugs disassembled (set 2) or mounted (set 3) were then compared.

Sets of tests 2 and 3 were performed in two different engines to evaluate the validity of the technique: the bench engine already used in set 1 and the engine of the collection car, that was kept mounted in the car.

Fig. 2. AE sensors location on a Renault AG1 engine © MNAM, 2018

IV. RESULTS

The feature used to extract the mechanical and air compression signature of the engine in 'cold test' conditions is the Root Means Square of the AE signals (AE rms) for every 10 ms period. This feature is related with the AE signal energy generated, for example, by sliding friction processes in contact pairs [3].

Fig. 3 shows the time evolution of the AE rms of the cylinder sensor -1- (a), and the angular position (b) and the rotational speed (c) of the crankshaft. In Fig. 3b, the crankshaft angular position is related with the thermodynamic cycle (720° or two complete crankshaft revolutions). When the first piston is at the Top Dead Centre (TDC) position, the rotation assumes 0°, 360° or 720° values. It can be seen that the test starts slightly before the piston passes by the TDC, then the crankshaft is rotated four revolutions, and finally extents its movement a little longer. Fig. 3c is the time derivative of the curve in Fig. 3b.

It can be observed that there is a high correlation between the AE rms feature and the crankshaft angular position and, consequently, on the relative motion of the piston to the cylinder. Minimum values of the AE rms occur at Top and Bottom Dead Centres (TDC and BDC) of both pistons, while maximum values occur at mid position between TDC and BDC where the piston speeds are maxima. This result indicates that the main source of AE waves is the sliding friction between the piston rings and the cylinder liners. Another result to be highlighted is that the crankshaft rotational speed along the test is not constant, which is due to the way the motion is driven (i.e. manually) and the variable resistance torque of the engine during its motion.

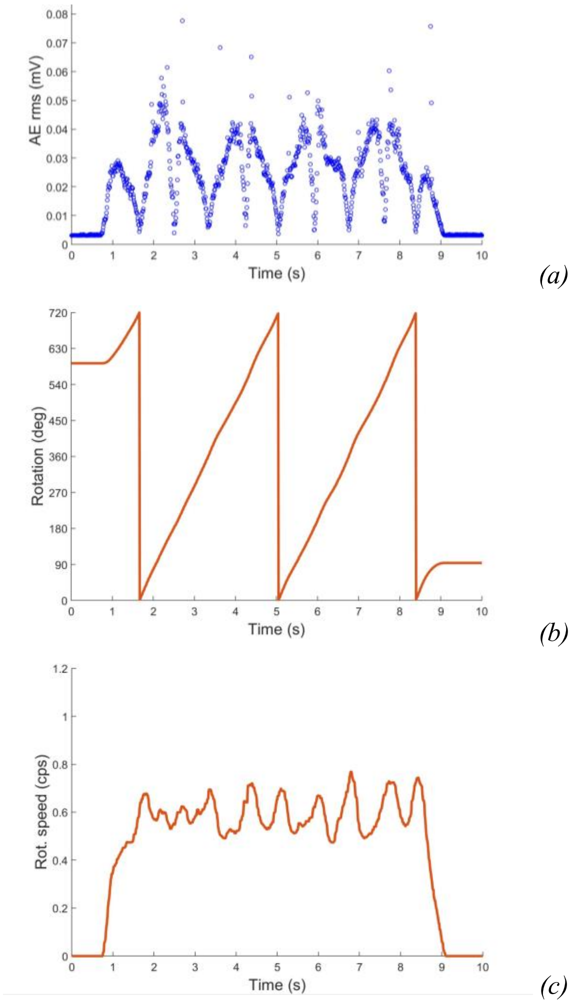


Fig. 3. Time evolution of (a) AE rms signal of sensor 1; (b) crankshaft angular position; (c) crankshaft rotational speed

In order to be able to compare AE rms feature at different positions along the same test and between different tests, a normalisation of the AE rms feature to a defined crankshaft rotational speed of 0.5 cps is performed. This speed is selected as it can be easily reached in 'cold tests' with and without air compression inside the cylinders. To transform the AE rms from the measured signal to the normalised speed, a proportional relationship described by eq. 1 is applied every 10 ms interval. Where, $n_{meas.}(t)$ is the measured crankshaft rotational speed (in cps) for the corresponding time interval. This transformation is based on the results from Fan et al. [3] who state that the AE energy generated during sliding friction is proportional to the relative speed between contacting solids. This result has been confirmed, for the range of speeds tested, by observing the AE rms from measured signals as a function of the speed at different crankshaft positions (See Fig. 4).

$$AE_{rms,norm}(t) = AE_{rms,meas.}(t)\frac{0.5\ cps}{n_{meas.(t)}} \qquad (1)$$

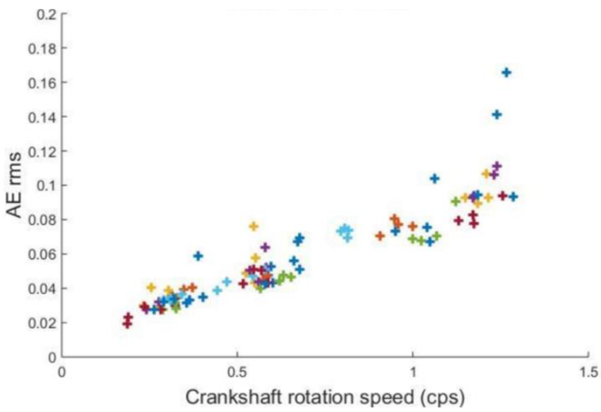
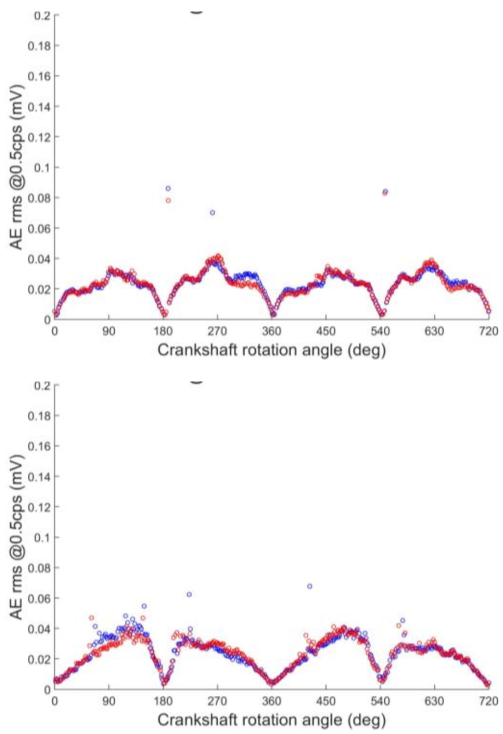


Fig. 4. AE rms signal of sensor -3- vs crankshaft rotational speed at 60° from TDC



(a)

(b)

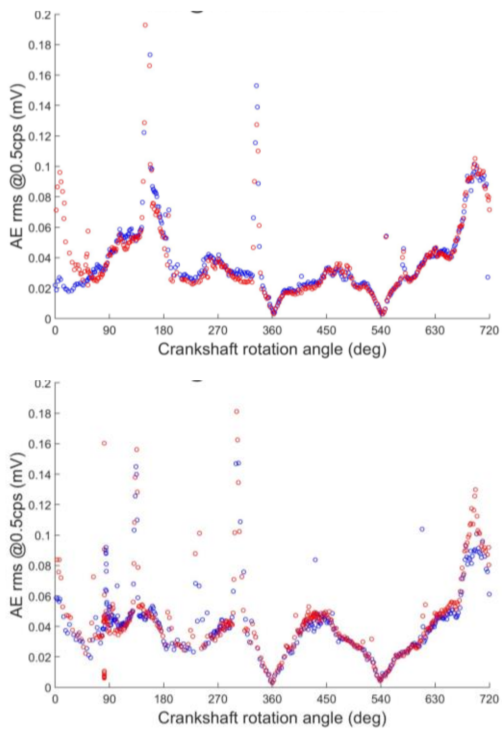
Fig. 5. Normalised AE rms signal of sensor -1- when no spark plugs are mounted: (a) bench engine; (b) collection engine

The normalised AE rms signals of the cylinder sensor -1- against the crankshaft angular position are plotted in Fig. 5 for two different engines: (a) the collection car engine and (b) the bench engine.

The crankshaft rotation evolves for two complete thermodynamic cycles (0-720°) -first cycle in blue and second cycle in red-, corresponding to four full revolutions of the crankshaft. The TDC of cylinders 1 and 2 correspond to 0° and 180° rotation, respectively. Both pistons complete four back and forth reciprocating motions. Every pass through the TDC and the BDC corresponds to a change in speed direction, where the piston speed is null. At those points the AE rms is almost zero, which confirms that the main source of AE events in the cylinder block is due to the sliding friction events between the piston rings and the cylinder liner. The absence of air compression inside the cylinders prevents, in those cases, the generation of AE waves from air flows.

Results are clearly reproducible for each engine when the normalised AE rms is taken into account. Those results are the mechanical signature (in absence of air compression) of the engine condition. It is clear that a mechanical signature is representative of a unique engine.

The normalised AE rms signals of the sensor 1 when the spark plugs are mounted, and then air is compressed inside the cylinders, are plotted in Fig. 6 for the two previously tested engines.



(a)

(b)

Fig. 6. Normalised AE rms signal of sensor -1- when spark plugs are mounted: (a) bench engine; (b) collection engine

Two main differences can be observed between results with (Fig. 6) and without (Fig. 5) spark plugs. Firstly, a clear increase of the AE rms level around the positions 90-180° and 630-720°, which are associated to the compression phase in the second and first cylinder, respectively. Secondly, some punctual spiky AE events that are related to valve opening and closing operations. Those signals are the combined mechanical and airflow signature of the engine conditions.

A deeper analysis of the data in Fig. 6 allows detecting a failure in the valve system of the collection engine. Fig. 6.a shows the AE rms signal evolution, where the signal generated by the airflows in the compression phase and valve operation is added to the mechanical signature (Fig. 5.a). Spiky signals are quite similar in shape and level, and the signals from compression phases of both cylinders are also analogous. However, in Fig. 6.b the signal of the compression phase of the second cylinder (between 90-180°) is significantly different (in shape and level) than the signal of the compression phase of the first cylinder (between 630-720°). A specific test performed to check the air tightness of the second cylinder highlighted a fault in the seat of the intake valve, leading to a loss in compression of around 35%.

V. CONCLUSIONS

A diagnostic tool based on AE measurements is being developed to help conservation-restoration technicians in reactivating historical vehicle's engines. This new tool will provide new and more objective diagnostic features free of human subjective evaluation. By performing 'cold tests' at initial reactivation stages, avoiding to damage the heritage objects, the mechanical signature of the engine condition can be obtained from proper AE measurements.

To collect reliable AE signals and for each type of engine, a preliminary study to locate precisely the AE sensors must be performed. The proper location of the AE sensors will provide appropriate signatures in order to perform a correct diagnostic of the engine condition.

When using AE rms features, the influence of the crankshaft rotational speed in the signal levels must be taken into account. In this work, and for the range of speeds used in the tests, a proportional correlation was applied to normalise the AE rms signal. This normalization procedure gave a good reproducibility of the obtained signals. The use of a controlled speed system for driving the engine motion or the use of other analytical techniques in the frequency or time-frequency domain can help avoiding the problem of having non-constant rotational speeds.

Preliminary results show that performing cold test using this AE technique is a promising tool to detect some malfunctions (such as air leakages in the valves) by applying adequate treatment procedures to the AE features obtained from the mechanical signatures of the engines.

Another interesting use of this technique is during the future maintenance procedure of the analysed engines. Once a reliable signature of the proper condition of an engine is registered, this diagnostic tool can be used to compare or analyse the evolution of the future engine's signatures with the reference one. Therefore, a database of the engines of an existing collection should be created and stored for future comparisons.

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