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Review

Vibro-acoustic condition monitoring of Internal Combustion Engines: A critical review of existing techniques

S. Delvecchio [a,*], P. Bonfiglio [b], F. Pompoli [b]

[a] Siemens Industry Software s.r.l, Viale Pietro ed Alberto Pirelli 10, I-20126 Milano, Italy
[b] Engineering Department in Ferrara, Università degli Studi di Ferrara, Via Saragat 1, I-44122 Ferrara, Italy

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ABSTRACT

This paper deals with the state-of-the-art strategies and techniques based on vibro-acoustic signals that can monitor and diagnose malfunctions in Internal Combustion Engines (ICEs) under both test bench and vehicle operating conditions. Over recent years, several authors have summarized what is known in critical reviews mainly focused on reciprocating machines in general or on specific signal processing techniques: no attempts to deal with IC engine condition monitoring have been made. This paper first gives a brief summary of the generation of sound and vibration in ICEs in order to place further discussion on fault vibro-acoustic diagnosis in context. An overview of the monitoring and diagnostic techniques described in literature using both vibration and acoustic signals is also provided. Different faulty conditions are described which affect combustion, mechanics and the aerodynamics of ICEs. The importance of measuring acoustic signals, as opposed to vibration signals, is due since the former seem to be more suitable for implementation on on-board monitoring systems in view of their non-intrusive behaviour, capability in simultaneously capturing signatures from several mechanical components and because of the possibility of detecting faults affecting airborne transmission paths.

In view of the recent needs of the industry to (–) optimize component structural durability adopting long-life cycles, (–) verify the engine final status at the end of the assembly line and (–) reduce the maintenance costs monitoring the ICE life during vehicle operations, monitoring and diagnosing system requests are continuously growing up. The present review can be considered a useful guideline for test engineers in understanding which types of fault can be diagnosed by using vibro-acoustic signals in sufficient time in both test bench and operating conditions and which transducer and signal processing technique (of which the essential background theory is here reported) could be considered the most reliable and informative to be implemented for the fault in question.

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* Corresponding author.
E-mail address: simonedelvecchio.nvh@gmail.com (S. Delvecchio).

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1. Introduction

The detection of faults and the diagnosis of Internal Combustion Engines (ICEs) are not simple tasks due to the complexity of such engines. Both detection and diagnosis activities could be performed using different strategies depending on operating conditions: test bench or vehicle (VICE, i.e. Vehicle with Internal Combustion Engines) operating conditions. During test-bench operations, information about engine status could be obtained by using (in order of priority) performance analysis, oil analysis, visual inspection, vibration and acoustic analysis. During VICE driving operations, a good strategy could be to monitor the ICE before losing performance or reaching mechanical failure. This could help the user to reduce the maintenance costs and/or to plane the maintenance actions in a more reliable way. For this purpose vibration and acoustic analysis represent informative and powerful tools for detecting faults at an early stage.

The vibrations and acoustics of reciprocating machinery such as Internal Combustion Engines, compressors and pumps are complex and difficult to analyse. Over the last few years the number of attempts to define signal processing strategies for condition monitoring has grown not only due to increases in computing calculation power but also due to the development of powerful signal processing techniques, i.e. cyclostationarity [1], and to recent attempts made by manufacturers in carrying out cold tests at the end of the assembly line [2–5]. The main difference between cold and hot tests is that hot tests are aimed at verifying engine performance while cold tests are aimed at verifying anomalies by means of torque, pressure, vibration and acoustic measurements. In addition to cold test measurements, a current challenge for manufacturers is to apply condition monitoring strategies for when a vehicle is being driven. This consists of monitoring the status of the ICE at different points of life (using steps involving the number of kilometres covered per year or years of life) to detect faults at an early stage and advise the user to have the vehicle checked before a failure appears and/or the vehicle loses performance.

In this context, acoustic signals could be an advantage as regards vibration since their non-intrusive behaviour allows the possibility of capturing superimposed signals from more than one component and the chance of detecting faults affecting pure airborne path transmission. Moreover, the recent development of low cost MEMS-technology microphones can help the acoustic monitoring technology to be implemented in on-board systems. On the other hand the acoustic signals are obviously more affected by environmental background noise that can mask the signal of interest. For vehicle driving operations, a robust monitoring implementation scheme could involve: (1) the signal acquisition; (2) several post-processing operations such as the correct selection of time histories, averaging and digital filtering to capture the signal of interest; (3) the implementation of signal processing techniques taking into account the characteristics of the signal and the type of machine/mechanical component from which the signal is being measured (i.e. rotating or alternative machines with simple or complex mechanisms); (4) extraction of several features that have to be analysed to assess the physical state of the ICE or to detect some incipient defects and determine the causes of their presence.

The purpose of this study is to review this entire monitoring procedure based on vibro-acoustic experimental studies that have been carried out in literature. In this context the final output of this research could be a useful guideline for test engineers in understanding which types of fault can be diagnosed by using vibro-acoustic signals at early stage and which signal processing technique could be considered the most reliable and informative to be implemented for the fault in question and for its specific transmission path to the receiver.

Several existing reviews on condition monitoring, fault diagnosis and prognostics deal generically with rotating machines [6–9]. In particular, [9] represents an advance in treating prognostic techniques for non-stationary and non-linear rotating system. On the other hand, some critical resumes have focused on the different capabilities in diagnostic procedures of specific signal processing techniques [10–13]. In addition, [14] represents the first interesting attempt to review both vibration and acoustic signal processing and confirms that acoustic signals are still used less than vibration signals for diagnostic purposes. Concerning ICEs, an interesting review is carried out in [15] in which N.B. Jones collect data about common faults, fault mechanisms and their effects on engine performance describing several diagnostic methods based on wear, pressure, temperature and emission analyses rather than vibro-acoustic signals. Wear analysis, pressure, temperature and emission analyses can also be carried out together with vibro-acoustic analyses for validation purposes.

This study begins with presenting a review of the main sources of higher noise and vibration in Internal Combustion Engines (ICEs). This review can be considered a useful part towards understanding which source, in the event of a malfunction, can alter the mechanism of the generation of noise and how the alteration happens. Moreover this analysis gives some preliminary information on how to properly measure vibro-acoustic signals on ICEs.