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Potential of Acoustic Emission in Unsupervised Monitoring of Gas-Fuelled Engines

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Abstract: The aim of this paper is to scrutinise closely information that contains in the acoustic emission of a gas-fuelled engine and to define the potential of knock condition detection. The recently introduced technique of nonstationary system identification is investigated. At first, it utilises the wavelet transform to reveal time-frequency energy density of data. Then the modified version of singular value decomposition is applied to extract dominant frequency components from the data buried in background noise. The efficacy of knock feature extraction is investigated using three sources of data: in-cylinder pressure, engine structure vibration and engine noise sensed by a microphone.

Keywords: Engine Management, Safety, Filtering techniques, Detection Algorithms.

1. INTRODUCTION

Growing world fleet, strict regulations on exhaust gas emission imposed by IMO, and deterioration in the quality of marine fuels, force the shipping industry to search alternative solutions to a traditional Diesel engine propulsion plant. In this respect, the use of natural gas, whose main component is methane, as a fuel for ship's engine is a highly promising solution to meet challenges of the requested technical compliance. The application of gas-fuelled engines, both the dual-fuel and pure gas, is highly beneficial on tugs, cruise vessels and ferries, where the proportion of coastal area operation is high. In recent time, however, the gas-fuelled engines are beginning to spread on cargo vessels too.

Despite benefits provided by the gas-fuelled engines, occurrence of an abnormal combustion process, called 'knock', represents one of the major constraints on performance and efficiency. The knocking phenomenon in the gas-fuelled engines is the spontaneous ignition of air-fuel mixture resulting in fast pressure rise and oscillation that transmitted to the engine structure and may cause engine damage. Furthermore, the modern engines are calibrated to provide highest thermal efficiency at the account of reduced knock margins. Therefore, identification of knock condition onset and the evaluation of its intensity, prior to evolving into serious breakdowns are prerequisites for the efficient, reliable and safe operation of the gas-fuelled engines.

Owing to the fact that knocking phenomenon is related to cylinder pressure developed during combustion, the knock detection methods based on direct combustion pressure measurement are the most efficient and precise, see Cavina et al. (2006), Ker et al. (2007), Millo et al. (2010). However, the pressure sensors, being costly and alien to engine design outside a test bed, are not commonly used on production engines. On the other hand, oscillating pressure due to knock, induces vibration of engine cylinder block and head and these vibration signals, if properly processed can help to identify non-knocking and knocking conditions, see Akimoto et al.(2012), Duval et al. (2002). Nevertheless, knock induced structure vibrations are buried in mechanically induced vibrations and identification is only effective when the energy of knock is relatively large. Hence, it is difficult for the vibration based methods to detect knocking at an early stage. The last but not least domain, where the knock is showed up, is the engine acoustic emission (AE) which appears to have better signal-to-noise ratio. The AE based monitoring methods are non-intrusive and successful application is found in bearings incipient fault detection, as shown in Hiremath et al. (2014). In recent time the applicability of AE based monitoring methods to internal combustion engines has been demonstrated too. Thus, Li et al. (2001) and Yong et al. (2007) showed that the combustion related and mechanical system related components can be successfully recovered from engine noise even with rather small energy levels. Furthermore, combustion-related faults of different severity, as well as engine health condition change, can be identified from the analysis of the engine acoustic signal as shown in Albardor (2013), and Pontopiddan et al. (2003, 2006). Finally, Lowe et al. (2011) revealed that detection of the excessive knock operational regime of Diesel engine is possible using AE signal.

This paper addresses the problem of the knock combustion identification at the early stage by the non-intrusive method such as AE analysis. The recorded acoustic signal from the gas-fuelled engine is scrutinised closely with time-frequency analysis, and the obtained signal features are compared to those obtained from vibration and in-cylinder pressure signals.

2. TEST ENGINE AND INSTRUMENTATION

The test engine used in this study is the mass-produced AYG20L engine designed by Yanmar. The AYG20L is a

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four-stroke, high-speed engine that operates only on natural gas with a lean-mixture – Otto cycle. The engine is directly coupled to an alternator, which in turn is loaded by a bank of ballast resistors. A pre-chamber with a spark plug ignition provides a high-energy ignition source for the lean gas-air mixture in the combustion chamber.

For data acquisition, only one cylinder of the test engine was instrumented with sensors: a combustion pressure transducer, an accelerometer on the engine block, and a microphone at the intake port side. The engine was also equipped with a rotary encoder providing 0.5-degree resolution of crankshaft position. All signals were recorded simultaneously, providing for the synchronisation of crankshaft position and data samples. The test engine specification and measurement system layout are given in Fig. 1.

The extensive experimental data were collected during a joint experiment on knocking characteristics of the gas-fuelled engine as explained in Ichikawa et al. (2016). In this experiment, the various engine parameters were tuned to provoke knocking condition of varying severity, thereby providing a vast database for evaluating the AE features with respect to knocking intensity.

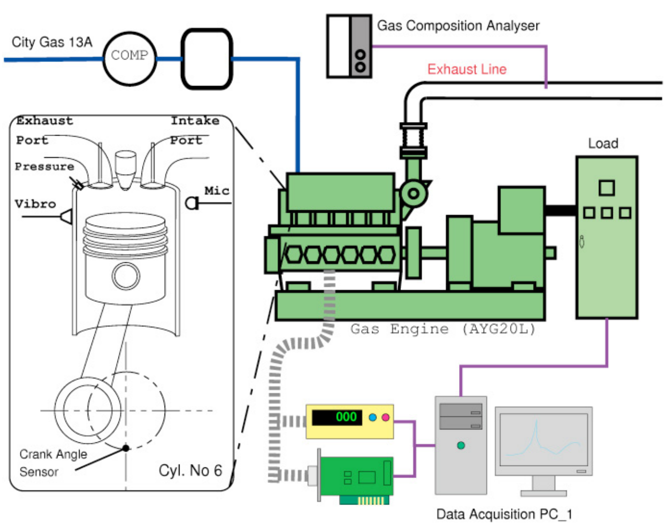


Fig.1. Vibration, Pressure and AE measurement points

3. KNOCKING CONDITION IDENTIFICATION

3.1 Definition and Properties

The knock phenomenon characterises abnormal combustion that initiates spontaneously in the combustion chamber of the engine. In normal combustion, the flame front of air-fuel mixture propagates, from the point of ignition, homogeneously towards opposite end of a cylinder charge (the end gas). However, unsteady temperature and pressure of air-fuel mixture may set the condition for self-ignition of unburned gas ahead of the propagating flame. Self-ignition may also start from 'hot spot' in the end gas. The resulting pressure impulses induce the propagation of the resonant pressure waves that are essentially acoustic as their amplitudes are small compared to the mean combustion pressure.

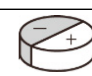
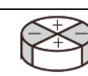
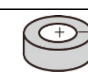
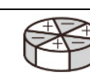
The expected fundamental frequencies can be estimated by using the analytical solution of the wave equation obtained in Draper (1934) for the cylindrical combustion chamber, and assuming that the height of combustion chamber is much smaller than the diameter it yields:

$$f_{m,n} \approx \frac{c\,\alpha_{m,n}}{D_p}, \quad \therefore c = \sqrt{kRT} \tag{1}$$

where c denotes the speed of sound in gas, D_p is the cylinder diameter, $\alpha_{m,n}$ is the wave number (determined from the Bessel's function), the indices m and n are integers denoting mode number, k is the specific heats ratio (is set to 1.34), R is the gas constant, and T is the burned gas temperature (an average value of 1800 K is assumed).

The calculated resonant frequencies for the first four modes are reported in Table 1 together with a graphical representation of the corresponding mode.

Table 1. The knocking modes fundamental frequencies

Mode				
$\alpha_{m,n}$	$\alpha_{1,0} = 0.59$	$\alpha_{2,0} = 0.97$	$\alpha_{0,1} = 1.22$	$\alpha_{3,0} = 1.34$
f, kHz	3.2	5.26	6.6	7.3

The properties of knock, identified in pressure signal, were outlined in numerous studies (see Millo et al. (2010), and Cavina et al. (2006)), as well as were confirmed in experiments done by the authors. The most important points can be jotted down as follows: knock appears over a short combustion period; interaction between the flame front and spontaneous ignition spots generally affects the knock amplitude; the main portion of the knock energy is contained within the lowest mode $\alpha_{1,0}$; last but not least, mode frequency changes with the piston position, combustion temperature and composition of the end gas. The last statement points out to the non-stationary nature of knock event and justifies certain difficulties in knock detection as shown in Akimoto et al.(2012), and Duval et al.(2002).

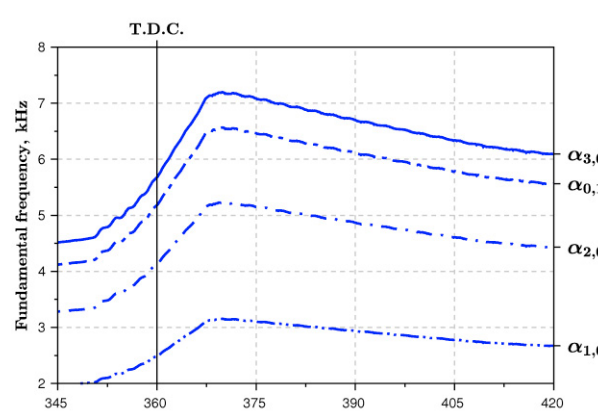


Fig.2. Non-stationarity of knock modes frequency