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Time and frequency analyses of dual-fuel engine block vibration

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ABSTRACT

A single-point time, frequency experimental analyses have been carried out to scrutinize the engine-block vibration of a LPG-diesel, dual-fuel engine. A liquefied petroleum gas (LPG) has been used as the main fuel in a diesel engine where diesel fuel has been used as a pilot fuel to ignite the gaseous fuel. The results of the dual-fuel engine vibrations are compared to the vibrations of base diesel engine as a benchmark. The engine cylinder head vibration has been measured at different engine operating conditions of load, speed, injection timing and compressions ratio. Fast-Fourier-Transform (FFT), Short Time Fourier Transform (STFT) and root mean square of vibration signal have been calculated for the vibration signal for both engines. It has been found that the dual-fuel engine exhibits less vibration than the diesel engine. Results show that the vibration of dual-fuel engine is distributed over a narrow range of frequencies compared with diesel engine. These results of low vibrational levels for the dual-fuel engines, as compared with the diesel engines under similar operating conditions, would encourage us to further investigate the potential of using dual-fuel engines for better environmental and mechanical performance.

1. Introduction

Engine vibration is critical to the overall engine performance [1], engine life and passengers comfort [2]. Engine vibration is usually transmitted through engine mounts, chassis, seat surfaces, backrests, and floor to passengers and cause human whole-body vibration. Most whole-body vibration exposures are associated with transportation where vehicle drivers or passengers are exposed to mechanical disturbances and impacts while traveling. Whole-body vibration can affect comfort, performance, and health, depending on the magnitude, waveform, and exposure times. People are most sensitive to whole-body vibration within the frequency range of 1–20 Hz, although many measurements include higher frequencies [2]. Motion sickness is concerned with frequencies below 1 Hz, while whole-body vibration is concerned with frequencies from about 1 to 100 Hz, and hand-transmitted vibration is associated with frequencies from about 8–1000 Hz. Vehicle engine vibrations are exhibited in all directions with some variations depending on number of cylinders, cylinder configuration, ignition order, balancing technology, type of engine supports and engine operating conditions such as speed, load, injection timing of fuel and spark timing [1].

Vibration and noise analyses have been used in many ways to improve engine operation. Borg et al. [3] have managed to reduce gasoline engine noise by about 5 dB using a direct injection scheme and by separating the high pressure pump and pipes noise and vibration from the main engine vibration during engine idling conditions. The application of short time Fourier transform (STFT) to measured vibrational acceleration of gasoline engine is found to identify clearly events such as valve impact, injector-pulses and engine knocking [4]. Diesel engine vibration signal is also used to diagnose some faults in diesel engines when compared to reference values [5]. Diesel engine vibration is analyzed by classical Fourier analysis and time-frequency analysis to define the degree of correlation between in-cylinder pressure and vibration signals of a diesel engine [6]. Carlucci et al. [7] have used time-frequency analysis of block vibration to study the effect of injection timing and pressure on the block vibration. It has been proved that injection pressure and the injected fuel mount affect the vibration signals in a non-clear manner but the relation between the combustion development in diesel engine, the injection system and the block vibration is evident [7–8]. It has been also shown that the oscillating performance of the inner-cylinder gas excitation is the main excitation to diesel engine vibration. However, the mechanical and fluid impacts inside the engine form the high-frequency excitations [9]. Hafidi et al. have measured diesel engine vibration at the engine and powertrain mounts [10]. Their

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Nomenclature

BMEP	Brake mean effective pressure, kPa
LPG	Liquefied petroleum gas
FFT	Fast Fourier Transform
STFT	Short Time Fourier Transform
RMS	Root mean square value
RPM	Engine speed
BDC/TDC	Bottom/top dead centers
N	Engine speed, rev/s
IT	Liquid fuel injection timing, degrees BTDC
IVO/IVC	Intake valve opening/closure
EVO/EVC	Exhaust valve opening/closure
IDI	Indirect injection diesel engine
CR	Engine compression ratio

six-cylinder engine is attached to the frame through three resilient mounts. It is shown that the third harmonic (3 times the frequency of engine rotation) is dominant in all studied cases.

Vibration of diesel engine when some biodiesel fuels are used [11–12] have been also investigated and compared to diesel engines. Vibration analyses are performed for a diesel engine using biodiesel, derived from canola and soybean, and pure diesel fuel [11]. The vibration signals are collected at the front of the engine and in three orthogonal directions. The vibration levels significantly varied with the fuel blends. Statistical analysis showed that blend of 20% and 40% of biodiesel have the lowest vibration levels compared to pure diesel and all other blend percentages. It is also concluded that for different engine speeds, vibration is always consistent with power-torque curve. The FFT frequency range of 1–2000 Hz was used to monitor the diesel engine vibration for both diesel and methyl ester of pungamia oil. It has been shown that the overall vibration of the engine is reduced with the biofuel. [12]. Some researchers have found that adding Hydrogen of about 10% mass has reduced the combustion noise and engine vibration measured in a diesel engine [1,13]. However, Szwaja has found that reducing the combustion rate is a good means to reduce the combustion noise and vibration in a spark ignition engine that uses hydrogen as the main fuel [14].

One of the current alternative gaseous fuels for diesel engines is the natural gas or liquefied petroleum gas LPG. The use of natural gas and other gaseous fuels in diesel engines has been used for long time due to their economic and environmental benefits. Engine performance (torque, power, and fuel consumption) and reliability of the dual-fuel engines are comparable to that of the diesel engines [15]. Dual-fuel engines use gaseous fuel admitted in the intake of the engine as the main fuel while liquid diesel fuel is used as a pilot fuel injected normally in very low quantity. Many previous works have been carried out to investigate the performance, exhaust emissions and engine noise of dual-fuel engines. However, the vibration analysis of such dual-fuel engines using natural gas or other gaseous fuels is not available, to the best of the authors' knowledge. One of the most critical parameters in the engine design and use is the engine block vibration especially when the gaseous fuel is used. Vibration stemmed from combustion of gaseous fuel inside the combustion chambers of the engine is of great importance and interest as this affects the engine and vehicle overall performance and reliability. It also affects the passengers' comfort when such engines get in use in vehicles.

The objective of this study is to carry out a vibration analysis of dual-fuel internal combustion engines. The acceleration of the engine block is measured and analyzed. The time-frequency analysis of the acceleration signal is accomplished by calculating the Fast Fourier Transform (FFT) or Short-Time Fourier Transform STFT. It also includes the root mean square of vibration amplitudes for the whole range of frequencies available. This work presents the time-frequency vibration analysis of a dual-fuel engine running on LPG as the main fuel and liquid diesel fuel as the pilot fuel and compares that engine to pure diesel fuel case. The engine operating and design parameters such as load speed, liquid fuel injection timing, and compression ratio are varied and their effects on the resulting vibrations are investigated. It has been found out that the dual-fuel engine exhibits less vibration than the diesel engine. It has been found also that the vibration of dual-fuel engine is distributed over a narrow range of frequencies compared with diesel engine. Detailed discussion of the measured vibrations over a wide range of frequencies and operating conditions is presented.

2. Experimental testing

The research engine used in the present study is the Ricardo E6 single-cylinder variable-compression indirect-injection diesel engine. The specifications of the engine are listed in Table 1. The engine cylinder head has a Ricardo Comet Mk V compression swirl combustion chamber. This type of combustion system consists of two parts. The swirl chamber in the head has a top half of spherical form and the lower half is a truncated cone, which communicates with the cylinder by means of a narrow passage or throat. The second part consists of special cavities cut into the crown of the piston. The engine is loaded by an electrical dynamometer rated at 22 kW and 420 V.

The engine is fully equipped with measurements of all operating parameters, combustion pressure, crank angle, and vibrational acceleration of the cylinder head. The pressure time history is measured by a water-cooled piezoelectric pressure transducer and crankshaft angle sensor connected to relevant amplifiers. The liquid fuel flow rate is measured digitally by a multi-function microprocessor-based fuel system, Compuflow System. The vibrational acceleration is measured using an ICP (Integrated Circuit Piezoelectric) accelerometer PCB 352A60 which has a good bandwidth from 5 Hz to 60 kHz. The accelerometer is then connected to an ICP sensor signal conditioner PCB 442C04. The signal conditioner has a built in circuit to remove DC component in the acceleration signal. Pressure, crank angle and acceleration signals are then connected to a data acquisition system which stores sensory data for further offline analysis. The data acquisition system includes a low pass filter to avoid aliasing, data acquisition card NI USB-6215 and a personal computer. A Labview code is written to view and store data. In addition, other engine parameters such as fuel flow rate, engine speed, load torque, and air, coolant, oil and exhaust temperatures are recorded for each experiment run.

Table 1
Engine specifications.

Model	Ricardo E6 – Diesel Version
Type	IDI with the pre-combustion chamber
Number of cylinders	1
Bore × stroke (mm)	76.2 × 111.1
Cycle	4-stroke
Compression ratio	Variable; up to 22
Maximum power (kW)	9, naturally aspirated
Maximum speed (RPM)	3000
Injection timing	Variable; 20–45 BTDC