Mechanical Systems and Signal Processing 116 (2019) 832–842

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

A virtual injection sensor by means of time frequency analysis

Alessandro Ferrari *, Federica Paolicelli

Energy Department, Politecnico di Torino, Italy

ARTICLE INFO

Article history:
Received 25 January 2018
Received in revised form 12 May 2018
Accepted 7 July 2018

Keywords:
Time frequency analysis
Spectrogram and mean instantaneous frequency
Injection system
Diesel engine
Injection virtual sensor

ABSTRACT

A time frequency analysis has been applied to an experimental pressure signal that is measured along a high-pressure pipe that connects the rail to an injector in a fuel injection system for diesel engines. An experimental test campaign has been carried out at a high-performance hydraulic rig for Common Rail systems.

The variations in the mean instantaneous frequency, which is calculated from a spectrogram of the experimental injector inlet pressure time histories, are related to key events pertaining to the injection phase. The physical meaning of these variations in the mean instantaneous frequency is identified through a comparison with the outcomes of a numerical simulation using a previously developed one-dimensional model of the injection system. This tool allows the lift of the mobile valves, the instantaneous injected flow-rate and the pressure transients inside the injector to be predicted accurately.

The objective of the research has been to realize a virtual sensor to detect the opening and closure instants of the mobile valves within the injector, on the basis of the pattern of the mean instantaneous frequency trace. The realized virtual sensor has been applied to the analysis of both single and multiple injection events.

1. Introduction

Modern diesel engines require that the injection rate of fuel in the combustion chamber is dosed with high accuracy to ensure an optimized heat release rate pattern that can minimize fuel consumption, engine out emissions and combustion noise. Great attention is being paid to NO_x and soot emissions to satisfy the new testing procedures and regulations, such as the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) [1] and the Real Driving Emissions (RDE) [2].

The development of diagnostic and real time monitoring techniques has mainly concerned the combustion process for spark ignited and diesel engines. Researchers have elaborated several methodologies for the detection of knock [3,4] and cylinder misfire [5,6], for the reconstruction of the heat release rate (HRR) curve [7,8], as well as for the prediction of the ignition delay [9] and for the identification of the start of combustion (SOC) [10,11] and of the barycenter of combustion (MFB50) [12]. Most of the methods rely on the analysis of the in-cylinder pressure time-history or of the in-cylinder pressure derivative to recognize the main features of the combustion process (SOC, HRR peak value, MFB50 and EOC). The presence of significant oscillations in the combustion chamber pressure, when combustion occurs, has also been used to reveal the incidence of specific events by means of the application of Time-Frequency Analysis (TFA) techniques [13,14].

In a recent patent publication [15], the time derivatives of a pressure signal have been used for injection related diagnostic purposes. The authors of the patent propose a new configuration of the rail (split-rail) that would allow the use of the rail pressure signal to detect injection events in diesel engines.

* Corresponding author.
E-mail address: alessandro.ferrari@polito.it (A. Ferrari).

https://doi.org/10.1016/j.ymssp.2018.07.009
0888-3270/

Nomenclature

CR	Common Rail
DT	dwell time
E	energy
E_x	signal energy
EOC	end of combustion
ET	energizing time
F_x	Fourier transform
FMV	fuel-metering valve
G	fuel injection rate
f	frequency
HRR	heat release rate
h	window function
ICE	internal combustion engine
KMM	Kontinuierliches Mengenmessgerät (Continuous flow meter)
l	pilot-valve lift
MFB50	50% of burned mass fraction
MIF	mean instantaneous frequency
N	number of samples
n	discrete time
p	fuel pressure
S_x	spectrogram
STFT	Short-Time Fourier Transform
SOC	start of combustion
T	time interval
t	time
τ	central time instant of the window function
1D	one-dimensional

Subscripts

a	after injection
inj	injector, injected
m	main injection
min	minimum
nom	nominal
p	pilot injection
sim	simulation
0	initial value, reference value

In addition to this, other diagnostic investigations on the injection event have been carried out, based on the fuel spray evolution [16,17]. This type of analysis is advantageous for examining some characteristics of the phenomenon, such as spray penetration into the combustion chamber, spray angle, spray uniformity and the effects related to injector ageing, but it does not cover aspects related to the injected mass or to the timing of the key instants of the injection phase. Above all, the approach cannot be exploited to monitor engines under real conditions.

TFA has often been applied successfully for machinery fault detection and diagnosis purposes [18–20] since it is a powerful tool for the analysis of unsteady and impulsive signals. A TFA methodology, which is based on the analysis of slight variations in the rail pressure signal during an injection event, has been recently proposed [21] for the diagnosis of Common Rail injection systems. The scope was to establish whether an injection had occurred or not, and to identify any defective cylinders.

In the present work, a TFA methodology has been implemented to detect the timing of the main events of an injection by analysing the pressure variation measured along the pipe that connects the rail to the injector. This approach could be applied to real-time monitoring of the injector dynamics during both single and multiple injection events in diesel engines. The experimental pressure time-distribution detected along the rail-to-injector pipe was chosen for the analysis being sensitive to the dynamics of the injection phase inside the injector [22].

2. Experimental setup

The experimental tests have been carried out on a Common Rail System for diesel engines with a rail featuring an internal volume of 20 cm^3. A high-pressure rotary pump with a displacement of 700 mm^3 has been employed to deliver the