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Cylinder pressure reconstruction based on complex radial basis function networks from vibration and speed signals

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Abstract

Methods to measure and monitor the cylinder pressure in internal combustion engines can contribute to reduced fuel consumption, noise and exhaust emissions. As direct measurements of the cylinder pressure are expensive and not suitable for measurements in vehicles on the road indirect methods which measure cylinder pressure have great potential value. In this paper, a non-linear model based on complex radial basis function (RBF) networks is proposed for the reconstruction of in-cylinder pressure pulse waveforms. Input to the network is the Fourier transforms of both engine structure vibration and crankshaft speed fluctuation. The primary reason for the use of Fourier transforms is that different frequency regions of the signals are used for the reconstruction process. This approach also makes it easier to reduce the amount of information that is used as input to the RBF network. The complex RBF network was applied to measurements from a 6-cylinder ethanol powered diesel engine over a wide range of running conditions. Prediction accuracy was validated by comparing a number of parameters between the measured and predicted cylinder pressure waveform such as maximum pressure, maximum rate of pressure rise and indicated mean effective pressure. The performance of the network was also evaluated for a number of untrained running conditions that differ both in speed and load from the trained ones. The results for the validation set were comparable to the trained conditions.

Keywords: RBF network; Cylinder pressure; Pressure reconstruction; Engine performance assessment

1. Introduction

Combustion pressure waveform measurement and analysis plays an important role in the improvement of performance, emission control, noise control and condition monitoring in internal combustion engines. Direct measurement of the pressure inside the cylinder with a pressure transducer is not suitable outside laboratories due to a number of limitations. For direct measurements a high performance pressure transducer has to be used and the harsh environment in the cylinder causes the transducer to have a limited lifetime; which makes the method expensive. It is also hard to find a good place to mount pressure transducers and effort has to be made to avoid errors due to calibration, wave propagation, and deposits on the transducer. As a consequence,

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Nomenclature

y	output signal of the RBF network
$\mathbf{w}$	weight matrix
w_0	bias
w_k	weight vector that connects the kth centre to the output of the network
$\phi(\mathbf{u},\mathbf{t}_k)$	kth radial basis function
$\mathbf{u}$	input vector
$\mathbf{d}$	target matrix
$\mathbf{t}_k$	kth centre vector
K	number of centres
N	number of training sets
A_h	start point for the Hanning window
A_e	end point for the exponential window

efforts have been made over the last 20 years to find a stable and reliable method to reconstruct the pressure waveform from indirect measurements. Two different approaches have been investigated, vibration measurement-based reconstruction and crankshaft angular speed measurement-based reconstruction.

It has been shown that both vibration- and angular speed signals contain information about the cylinder pressure but mainly in different frequency regions [1,2]. Angular speed fluctuation comes from the low-frequency content of cylinder pressure as angular velocity is not as sensitive as structural vibrations to instantaneous pressure changes [2]. Vibration measurements, on the other hand, suffer from low signal-to-noise ratio at low frequencies, making the reconstruction of the compression/decompression phase of the combustion process uncertain. In both cases the relationships between cylinder pressure and vibration response and crankshaft speed is non-linear and changes with the running condition.

The objective of this paper is to derive and evaluate a non-linear model for the cylinder pressure reconstruction based on complex-valued radial basis function (RBF) network using both the vibration and speed signal. Earlier studies using RBF networks for the pressure reconstruction have shown the potential of RBF networks [3–5]. Input to the networks has either been the crankshaft speed signal (in time domain) [3,4] or the power spectrum of the engine structure vibration [5]. In the study presented in this paper the input to the network is the Fourier transforms of the vibration and speed signals. By using the Fourier transforms of the measured signals the amount of data can easily be reduced and the interesting frequencies for each measurement method be selected. The use of the complex Fourier transforms also simplifies the task for the RBF network since for example a small change in the phase for one frequency component will only affect that frequency component in the frequency domain while the shape of the signal can change significantly in the time domain.

The proposed method is derived and tested on a 6-cylinder ethanol powered diesel engine by comparing a few commonly used parameters of the pressure waveform was compared between the reconstructed and measured pressure waveform. The parameters are maximum pressure ($p_{\max}$) and its location, maximum pressure rise and its location, and indicated mean effective pressure (IMEP).

2. Background

2.1. Engine vibration measurements

The quick pressure change in a cylinder during combustion gives rise to engine structure vibrations. These vibrations contain information about the combustion process and can easily be measured; normally on the cylinder head or the engine block. Unfortunately the vibration signal also contains non-combustion related vibrations that decrease the signal-to-noise ratio. Examples of unwanted vibration sources are piston slap,