THE DIAGNOSTIC MODEL PROPOSITION OF THE ENGINE VIBRATION SIGNAL

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Abstract

Vibroacoustic signal of reciprocating engine carries diagnostic information that is not efficiently used because of complicated signal processing methods for separation of useful components and noise elimination. The measured vibrations are a mixture of periodic waves due to the rotating components and transient waves due to the reciprocating components of the engine and pressure forces. Engine vibrations may be described in several ways depend on the diagnostic purpose. For detecting non-uniform cylinder operation, for instance, the methods for rotating machines can be considered. Many transients occur in vibration signal of the combustion engine like exhaust and inlet valve operations, fuel injection, combustion, piston slap. To analyze them the time-frequency methods can be used. Diagnosing of some damages, like valve clearance changing or valve burning, can be done using the diagnostic model. This model should be rather simple and sensitive to mentioned damages. In modelling two approaches can be considered. The first one is based on the real physical parameters of the system. The second one is making the abstractive statistical model of signal with abstractive parameters. In the paper the autoregressive model is proposed. Identifying model is finding periodically time-varying coefficients of the equivalent filter. All the damages in the system make changes of the coefficients. The model presented in the paper is illustrated with the signal of spark ignition combustion engine.

Keywords: *vibroacoustic model, autoregressive model, combustion engine, valve vibration*

1. Introduction

Wearing of elements and small mechanical defects cause adjusting the control system to new parameters. Therefore, in many cases there may appear masking the mechanical defects through adaptive engine control systems. Example of such defects may be valves leakiness, their destruction or inappropriate valve clearance. These defects are hard to diagnose without making the inspection of the engine and dismantling it. Hence, the idea to use the vibroacoustic signal, which advantage is the noninvasiveness of the method.

The vibroacoustic signal currently is used in engine diagnostics only to evaluate knock combustion in spark ignition engines. Meanwhile it is a rich source of knowledge not only about the process of combustion, but also about various mechanical defects which happen in driving unit and which concern valves, clutch, gearbox. Current systems of vehicle on-board diagnostics OBD focus on ecological aspects, so on evaluation of the process of combustion. Also, among off-line systems of diagnostics there are no such which would detect mechanical defects. It was discovered that some mechanical defects were masked by electronic fuel injection and ignition control system [3]. Whereas the constant development of methods of the signal processing, and, on the other hand, availability of the microcontrollers and signal processors allow to make a very detailed analysis of the signal and separation of the frequency components all in a real time.

Developed vibroacoustic model of the internal combustion engine would serve the purpose of detecting mechanical defects in the driving unit of a vehicle. Modelling method should be universal, irrespective of the fact if it is the diesel engine or the spark ignition engine. There are a few methods of modelling the vibratory signal of the internal combustion engine depending on the diagnosed sub-assembly or process [6]. To observe the smooth running of the cylinders, for example, a few following harmonic components are monitored, meaning the low frequencies of the signal. In such case the signal can be described in a form of the Fourier's series. In other case, assuming that the responses of the system to various unitary forces, such as closing valves or the piston slap occur independently and in a specific sequence, the vibrations may be described as a sequence of transitional vibrations. Generally, it is a noisy signal and the vibration response is a convolution of the series of various forces and responses. Then, the statistic models appear to be useful as the autoregressive model described in the article with coefficients that change periodically.

2. Experimental results and analysis

The test was performed on four-cylinder spark ignition engine 1600 with multipoint injection. The vibration signal was measured by a piezoelectric sensor screwed on the head near fourth cylinder. During the experiment, in addition to vibration signal, two monitoring signals were also registered simultaneously, namely the digital signal of crankshaft position and the control ignition pulse from electronic control unit. With additional signals identifying the engine timing and transferring from time to crank shaft angular domain were possible. Fig. 1. shows the analysis of the vibration signal during one work cycle of the engine. It is cyclic repeatable signal with transient events from valve openings and closures, piston slaps and combustion pressure rises that make the vibration signal non-stationary. Vibration energy rises at moments of mentioned events (Fig. 1b). The sequence of transients events versus crankshaft position is shown on Fig. 1c.

For frequency analysis of such signal the Fourier transform is not enough because it detects predominating frequency components but information of time of their occurrence is lost. The short-time Fourier transform STFT is very useful in this case. It is defined as the Fourier transform of a windowed time signal for various positions of the window with can slide in time. It can be written for continuous and discrete signals as follows [7]:

$$y(t) = x(t) \cdot w(t)\,, \tag{1}$$

$$y(n) = x(n) \cdot w(n)\,, \tag{2}$$

$$X(\tau, f) = \int_{-\infty}^{+\infty} \left[x(t) \cdot w(t-\tau)\right] \cdot e^{-j2\pi ft}\, dt\,, \tag{3}$$

$$X(n, \lambda) = \int_{m=-\infty}^{m=+\infty} \left[x(n+m) \cdot w(m)\right] \cdot e^{-j\lambda m}\,, \tag{4}$$

where:

$x(t)$, $x(n)$ - signal waveform and signal sequence,
τ - time variable,
λ - frequency variable,
$w(t)$, $w(n)$ - window waveform and window sequence.

In the STFT the one-dimensional sequence $x(n)$, a function of a single discrete variable, is converted into a two-dimensional function of the time variable n, which is discrete, and the frequency variable λ. The STFT is invertible if the window has at least one nonzero sample.

Fig. 2 illustrates the fragment of vibration signal during inlet valve closing and its time-frequency analysis. It shows that the dominant component of valve closing response is 15 kHz but shows wide spectrum up to 50 kHz as well.

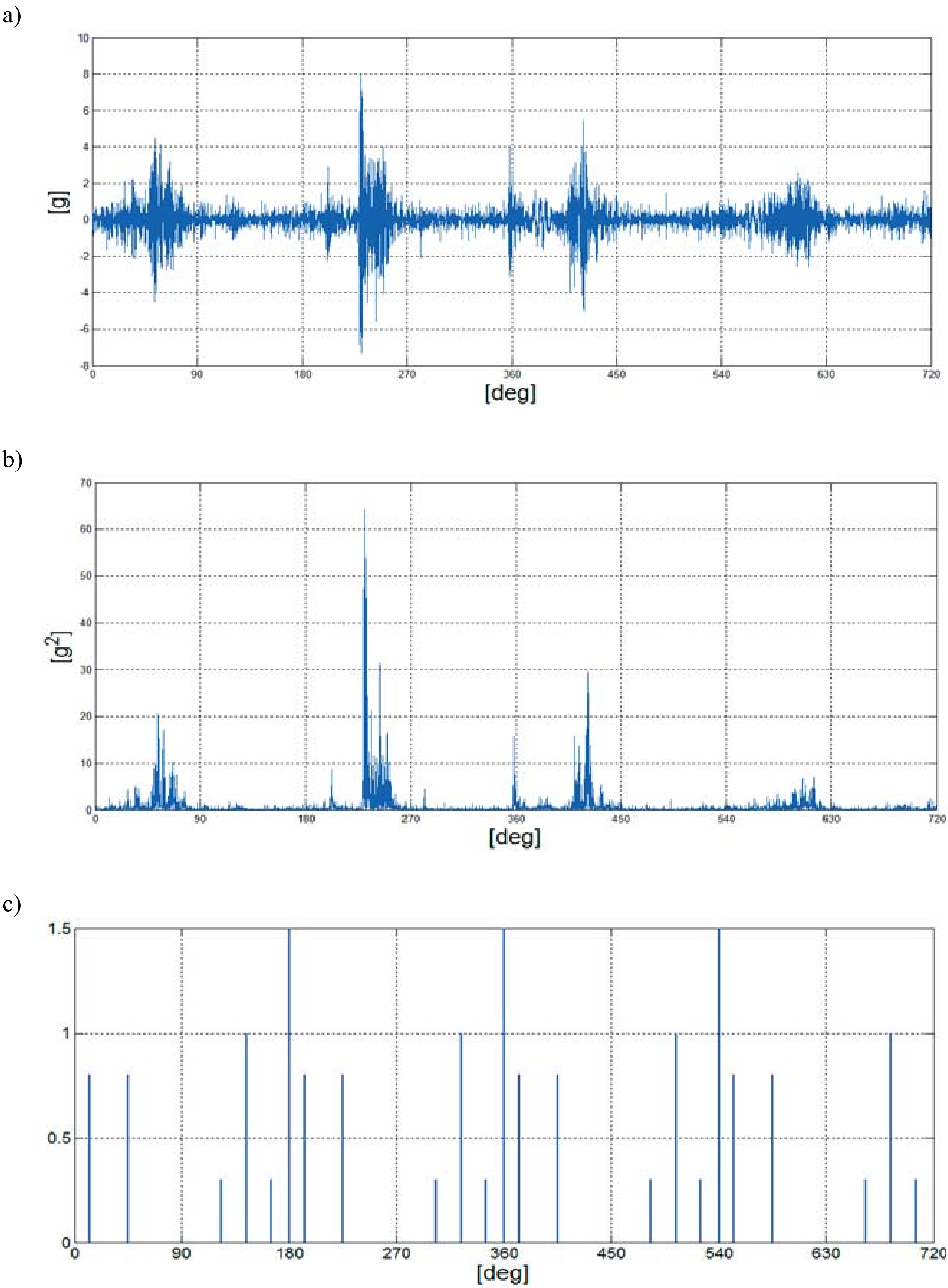
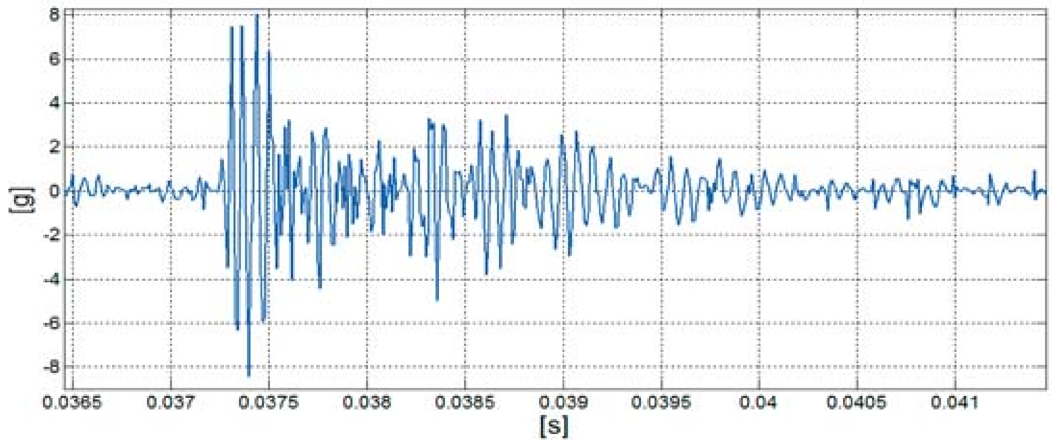


Fig. 1. Analysis of SI engine vibration during one work cycle acceleration signal instantenous vibration power vs. crankshaft angle theoretical angular positions of transients (TDC& BDC - .5, combustion start - 1.0, valves opening - 0.3, valves closing - 0.8)

a)



b)

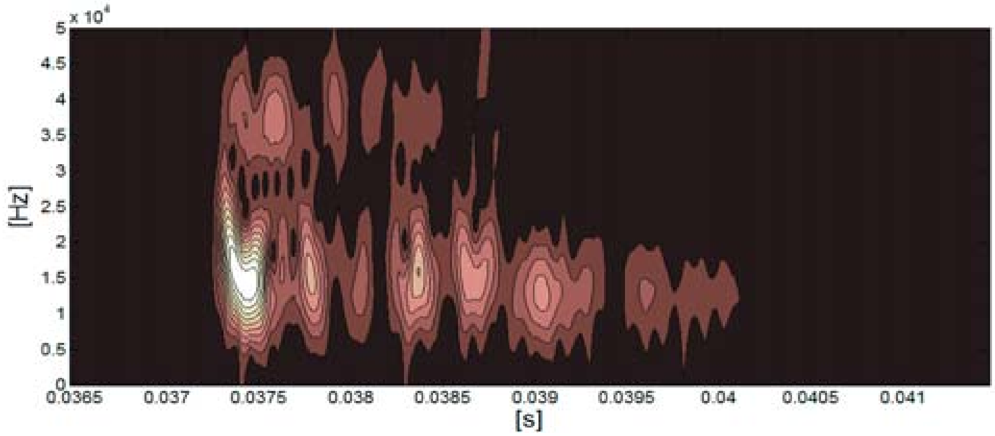


Fig. 2. Vibration response to inlet valve closing time waveform short time Fourier transform

3. Model proposal

Previous works [4,5] show, that it is possible to build a mathematical model of an engine valve, treating vibration signal as the response to the force unit, it was not too complicated but strong nonlinear. It is important that the engine vibration signal is poor quality. It is noisy and influenced with electrical interferences. Because it is proposed to build a statistical model with abstractive parameters that could be for instance periodically time-varying autoregressive model AR of the form [1]:

$$x(t) = \sum_{k=1}^{K(t)} a_k(t) \cdot x(t-\tau) + \varepsilon(t), \tag{5}$$

where:

$\varepsilon(t)$ - assumed white stationary prediction error,

$a_k(t) = a_k(t+T)$ - periodically time-varying autoregressive coefficients,

$K(t)$ - periodically time-varying order of model.

For discrete signals model can be written as:

$$x(n) = \sum_{k=1}^{K(n)} a_k(n) \cdot x(n-m) + \varepsilon(n), \tag{6}$$

where:

n - the number of the signal sample.

Really, such model can be realized using the equivalent filter described with the transfer function:

$$H(z) = \frac{1}{A(z)}, \tag{7}$$

where:

$$A(z) = 1 + \sum_{k=1}^{K} a_k \cdot z^{-k}, \tag{8}$$

z^{-1} - unit delay.

The filter is driven by a zero-mean value white noise [2] (Fig. 3).

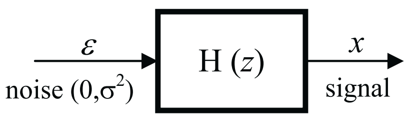


Fig. 3. Linear system driven by a zero-mean white noise

Choosing among digital filters the infinite impulse response IIR filter can be taken because of smaller number of the a_k coefficients at the same order of the filter. The structure of the 10th order IIR filter is illustrated in Fig. 4.

The order $K(t)$ of the filter and the number of coefficients of the autoregressive model is related to the number of dominant sinusoidal sources in the vibration signal conditioned on each angular position. Fig. 5 shows engine vibration waveform during inlet valve closing (dotted line) and the simulated signal (solid line) with model-filter with the order $K = 100$. The time-window contains 200 samples, that is 2 milliseconds. It is showed that the vibration signal can be well identified with this method.

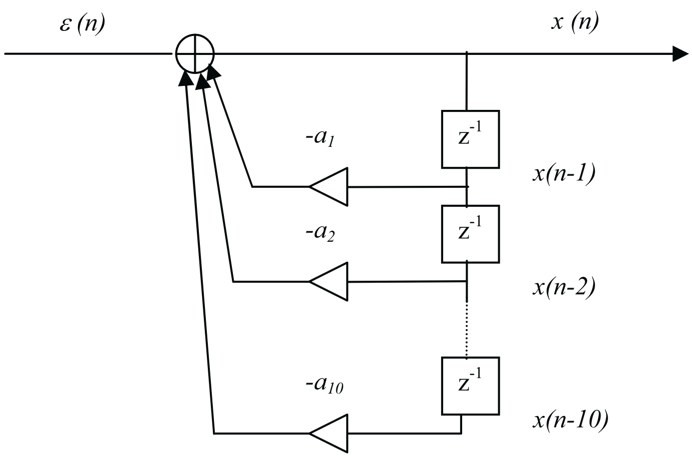


Fig. 4. The diagram of the model-filter

Next, the influence of the engine speed on the vibration signal was investigated. The comparison of vibration response to inlet valve closing at 1500 rpm and 2500 rpm is shown in Fig. 6. In the beginning phase both signals are identical and next they became stochastic. The coefficients of the equivalent filter a_k in both cases are drawn in Fig. 7. Their sequence is similar especially in the beginning phase, at the closure moment.

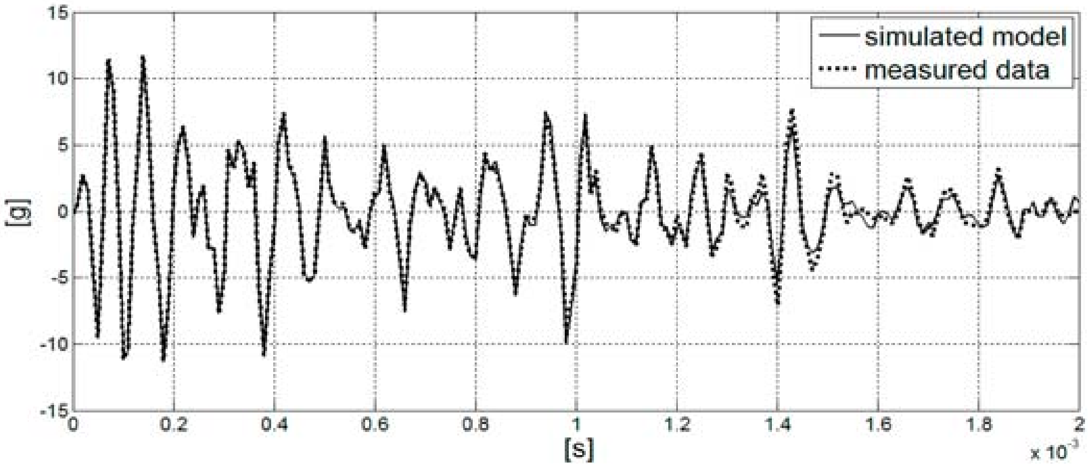


Fig. 5. Time window for inlet valve closing - measured data and simulated AR model

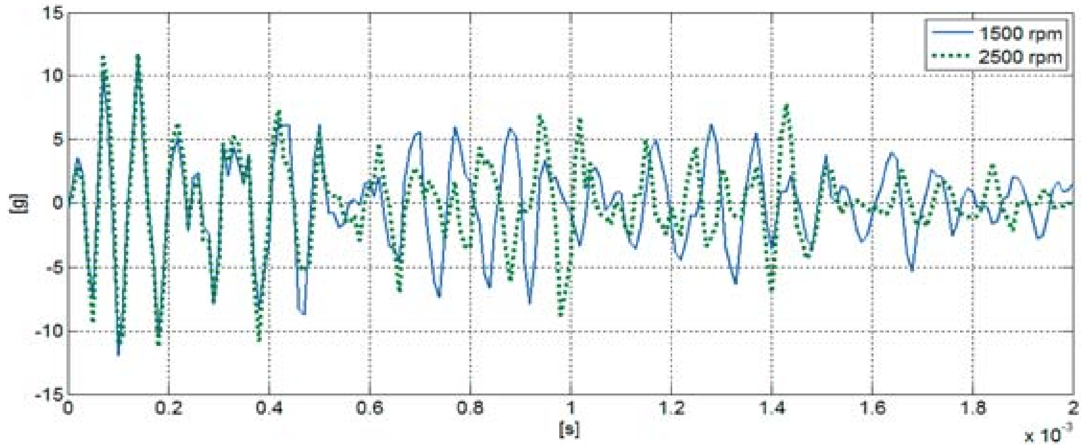


Fig. 6. Vibration response to inlet valve closing for the speeds 1500 rpm and 2500 rpm at the same load

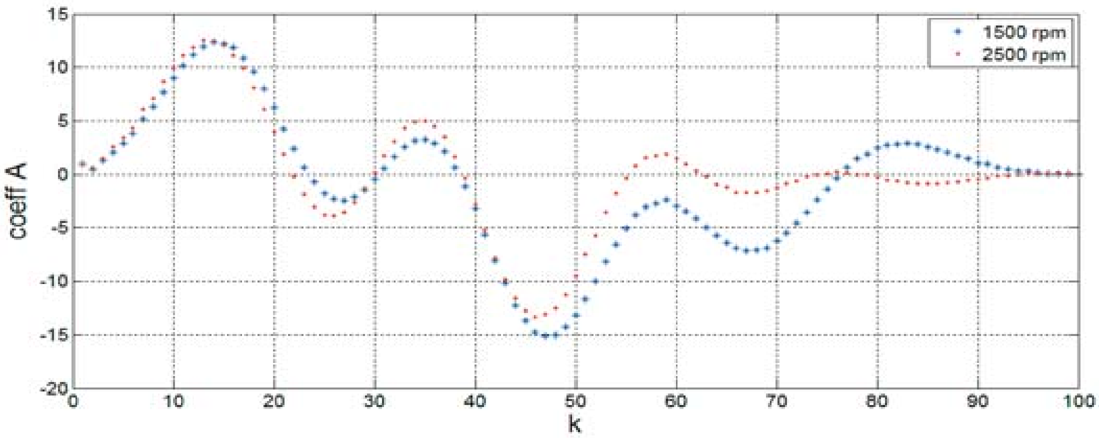


Fig.7. Equivalent filter coefficients a_k identified for inlet valve closing (see Fig.6)

4. Conclusion

In the article there was presented the proposal of modelling of spark ignition engine vibrations by means of abstract autoregressive model. Advantage of using such modelling is the possibility of working with signal of low signal to noise ratio, what when concerning signals which are registered on a vehicle engine is very important. The time-frequency analysis indicated the non-stationarities of the signal. Because of the limited length of the article the model was presented based on an example of closing the inlet valve of the engine. Analogically, the procedures were carried out for the whole cycle of the engine work, moving the time window of succeeding angle positions. For each position there must be settled an order of filter strictly connected with the number of predominating components in a given window. Algorithm may seem to be complicated but it can be automated. The constant development of methods of digital signal processing and DSP devices allows for an easy implementation of the model using a signal processor.

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