TYRE PRESSURE MONITORING WITH WAVELET-TRANSFORM

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The Tire Pressure Monitoring System (TPMS) is considered to be a widespread system in automotive industry. It has two basic aspects of view – direct and indirect. The first one uses pressure sensors while the second one uses the wheel speed signals of the ESP system on board to make an estimation of the pressure levels of the tyres.

The aim of this study is to find an indirect method which can be the competitor in digital signal processing of the most common and currently used Fourier-transform, and can be a match for the classic solution in complexity, necessary runtime and efficiency.

Another part of this research is to find an appropriate model to generate wheel speed signals that contain the additional information to detect the pressure change, moreover to develop a function library for the research to support the measurements and to analyze the results.

Keywords: tyre, pressure, DSP, indirect, wavelet, fourier, complexity

Introduction

Nowadays the Tyre Pressure Monitoring Systems (TPMS) are almost a standard equipment of mid-size passenger cars and this solution will be a mandatory feature for new cars in Europe starting 2012. The reason is simple. Due to some difference between the ideal and current pressure the traction and the stability can decrease dramatically and it can easily lead to an accident.

Methods

There are two methods to measure the pressure in the tyres.

The simplest one is to place intelligent pressure sensors in the tyres. Their radio signals are acquired and the pressure levels can either be displayed in the cockpit or be used by the driving stability system on board. This solution, called direct monitoring, is simple and reliable as long as the batteries of the sensors and the sensors themselves last.

If the signals of the wheel speed sensors *(Fig. 1)* of an ESP system contained some information about the actual pressure levels, this attribute could be used. The second method, called indirect monitoring, is based on this additional information in the speed signals. Moreover using sensors already available in the vehicle instead of new ones would reduce the costs.

Figure 1 : A wheels speed sensor of a stability system

Once the tyre is on the wheel and it's blown to a pressure level its circumference – apart from extreme driving manoeuvres and situations – can be considered to be constant. The only variant in this equation would be the tyre pressure. If it changes, the circumference changes as well. Since the wheel speed sensors measure the rotational speed *(ω)* of the wheel and that value is multiplied by a constant radius *(R)* parameter *(v = ω·R)* the real circumferential speeds of wheels with different pneumatic pressures and equal rotational speeds may be diverse. The wheel with the smallest circumference runs the most, the one with the highest runs the least. This behaviour can be observed and after a few calculations quite a good tyre pressure feedback can be given. The weakness of this solution is that it's less reliable as the vehicle speed increases.

Still in the indirect method the wheel speed signals can be observed from another point of view. The wheel can be considered as a spring-mass system. The spring is the flexible tyre the mass is the wheel base and some amount of the suspension. It starts oscillating while running on the road and as all such systems this one has

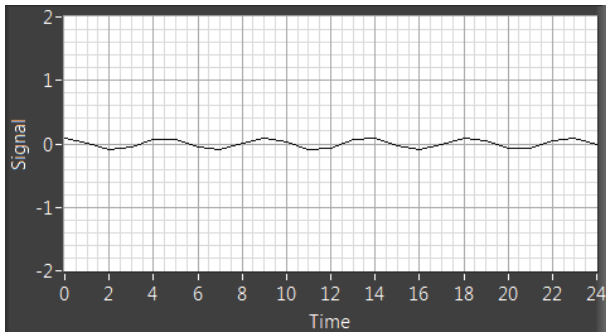an eigenfrequency which appears in the wheel speed signal too *(Fig. 2)*.

Figure 2: The wheel speed signal used in the experiments

This frequency depends on the amount of mass and the spring coefficient. The mass is usually constant so the only variant in this system is the tyre, mostly its pressure. The less pressure the tyre has the lower frequency appears and vice versa.

Current Solution

To gather the eigenfrequency of the mentioned system some kind of frequency analysis must be performed. The effective and obvious solution for this has been the Fourier-transform so far. It decomposes the signal to its constituent frequencies and returns the amplitudes of them. Its equivalent in digital world is the Fast Fourier-transform (FFT). Its result can easily be transformed to an exact form to find the most dominant components.
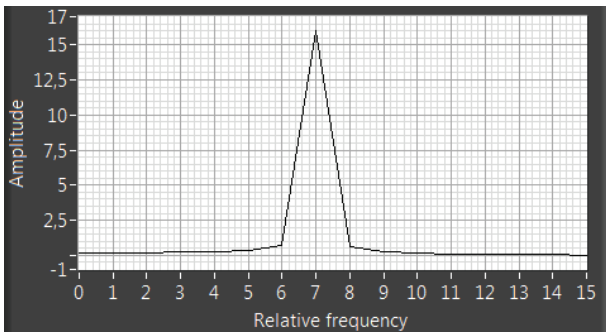

Figure 3: Partial result of a FFT

Once the transform has been performed the only work to do is to find the tyre's eigenfrequency in it which is usually in the range of 40–60 Hz. The example in *Fig. 3* has been calculated from 32 samples so as in the case of a FFT the result will have 32 values. The FFT is symmetric so only the half of the resulting array contains real information. Therefore there are only 16 values available in the image (0...15). The sampling frequency (fs) is 200 Hz so the highest detected frequency component at this sampling frequency is fs / 2 = 100 Hz. The range of 0–15 in the result means a frequency range from 0 to 100 Hz. The peak at 7 in the image means

$$f = (100 \text{ Hz}/16) \cdot 7 = 43.75 \text{ Hz}. \quad (1)$$

However there are only 16 values for 100 Hz which means there is 6.25 Hz for each segment. Therefore the actual eigenfrequency has to be calculated from all values instead of simply searching the maximal one. Of course for higher accuracy more samples are necessary.

Development

In this study the mentioned Fourier-transform has been replaced by the Wavelet-transform. More specifically by the Haar-transform which is one of the simplest variants of the Wavelet-transforms. It still contains the frequency information, but has time information in the result as well. To perform the Haar-transform the Haar-functions have to be calculated first. There always are as many Haar-functions as many samples. The exact form to describe all these functions is as follows:

$$h_0(t) = \frac{1}{\sqrt{N}} \quad (2)$$

$$h_k(t) = \frac{1}{\sqrt{N}} \begin{cases} 2^{p/2} & (q-1)/2^p \leq t < (q-0.5)/2^p \\ -2^{p/2} & (q-0.5)/2^p \leq t < q/2^p \\ 0 & otherwise \end{cases} \quad (3)$$

where $k = 1...N$; $p = [\log_2 k]$; $q = k - 2^p + 1$, the time is transformed to a $[0 ; 1]$ interval, so $0 \leq t \leq 1$.

A possible output for the Haar-transform can be seen in *Fig. 4*.

If performed on a noiseless signal, the domains in it are easy to see *(Fig. 5)*. All of them belong to different frequency components but the different values within them contain the time information.
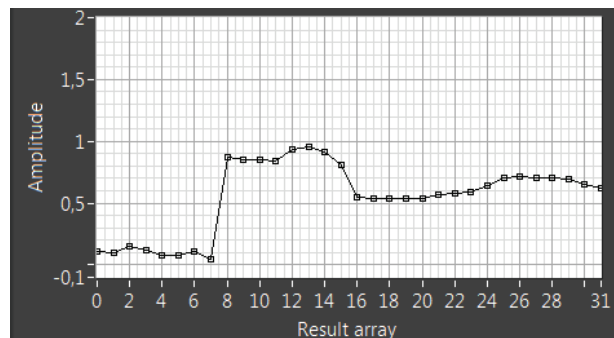

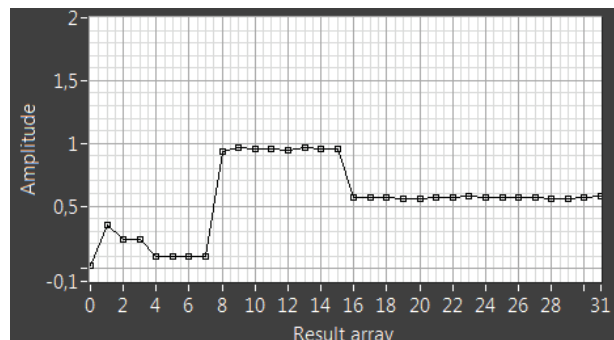*Figure 4:* Partial result of the Haar-transform

Figure 5: Domains in the Haar-transform

Table 1: Domains in the Haar-transform

Interval	f	T_{period}
0	DC component	∞
1	6.25 Hz	160 ms
2-3	12.5 Hz	80 ms
4-7	25 Hz	40 ms
8-15	50 Hz	20 ms
16-31	100 Hz	10 ms

The time information isn't important at this point due to the narrow time interval of the 32 samples.

$$f_s = 200 \text{ Hz} \rightarrow T_s = 5 \text{ ms} \rightarrow T_{32samples} = 160 \text{ ms} \quad (4)$$

Therefore only a mean value is calculated for each domain and the time information is cancelled. This way the disturbing noise effects can be damped a bit with a minimal loss of (unused) information.

Figure 6: Mean values for each domain

After the curve of the mean values is available *(Fig. 6)* the different frequency values can be paired with their corresponding curves. The actual eigenfrequency can be found based on a frequency-curve table and some interpolation.

The mean value of the domains described in *Table 1* can be seen in *Fig. 7* along the frequency range between 40 and 60 Hz. The correlation of the mean values and the different frequency values is obvious, but the highest frequency domains have to be used in the calculations to get a definite result.
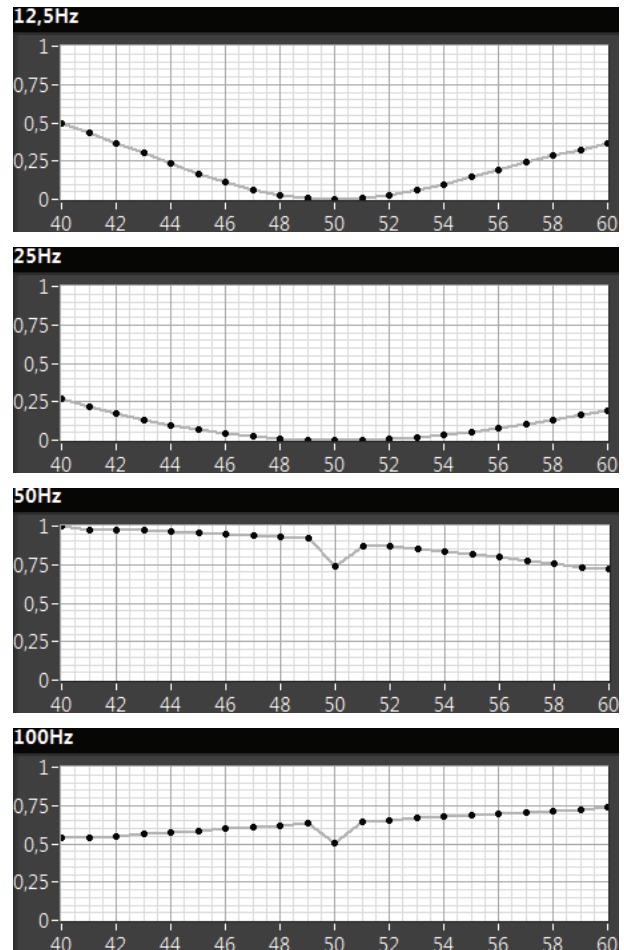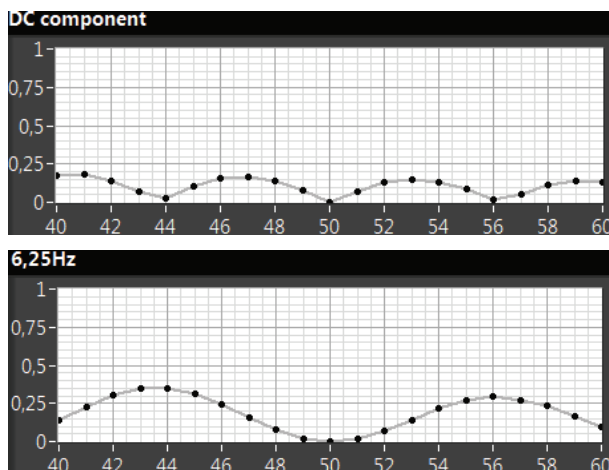

Figure 7: Mean values of domains for different frequencies

Benefits

The benefits of using the Wavelet-transform can be measured in milliseconds. There is a comparison of the necessary running times in the following charts. The running times of a basic Discrete Fourier-transform (DFT) and a Discrete Haar-transform (DHT) were compared.
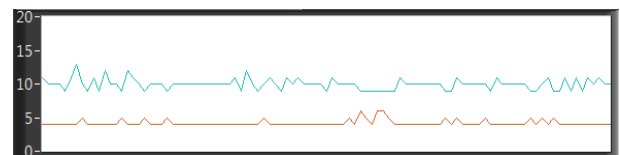

Figure 8: Runtime with 32 samples; red: DHT, blue: DFT

The experiment was performed on an average PC so the transforms had to be run 400 times to get quite an accurate measurement. This way the necessary time with 32 samples for DFT was ~10.5 ms, for DHT just above 4 ms. The new solution is 2,5 times faster already but let's see what would happen if the amount of samples was increased to 64:
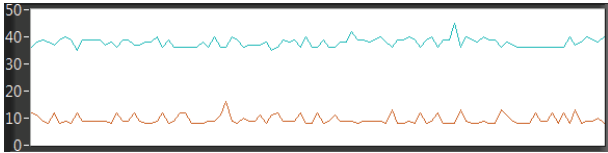
Figure 9: Runtime with 64 samples;
red: DHT, blue: DFT

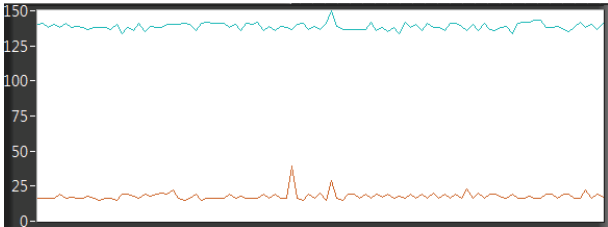The Haar-transform got about 4 times faster. Let's see the same situation with 128 samples:

Figure 10: Runtime with 128 samples;
red: DHT, blue: DFT

For this amount of samples the DHT is at least 7 times faster than the DFT.

The complexity of the DFT is considered to be $O(n \cdot \log n)$. The complexity of the DHT can be reduced to $O(n)$ with a minimal optimization:

Its generator functions – mostly at higher frequencies – contain intervals full of zeroes. These parts can be ignored due to the pointlessness of multiplications with zero. Otherwise the runtime would be similar to the runtime of the DFT.

This comparison may seem useless but the stability controller ECUs in vehicles are usually equipped with low-end CPUs. Therefore every reduced µs matters.
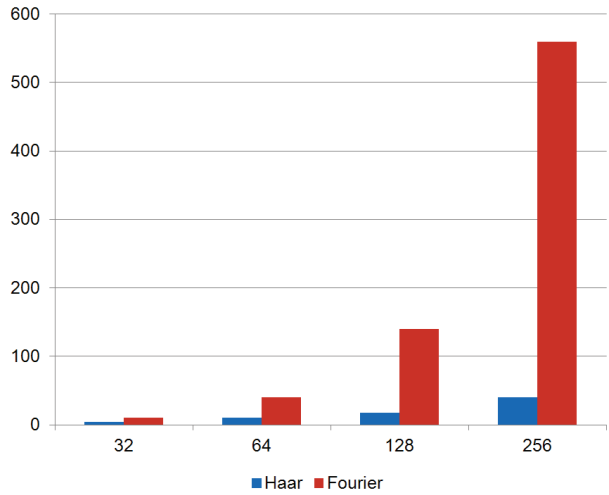

Figure 11: Runtime with 32, 64, 128 and 256 samples

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