ACOUSTIC TYRE MONITORING SYSTEM FOR DECREASING WHEEL-BASED ACCIDENTS

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SUMMARY

Tyre and wheel related malfunctions, such as tread separation, sudden loss of tyre pressure and locking of brakes, are a cause of numerous accidents daily all over the world. At best these accidents lead only to economical losses in form of material damage and delay while way too often they contribute to the growing number of road fatalities.

In this paper, a monitoring system under development aiming at prediction and detection of these malfunctions is described. Acoustic Tyre Monitoring System (ATMOS) monitors the sound of each wheel or set of wheels while the vehicle is on the road, providing processed real-time information in form of warning signals and recommendations to the driver as an integral part of Advanced Driver Assistance Systems (ADAS).

INTRODUCTION

Tread separation, sudden loss of tyre pressure and locking of brakes, among other tyre and wheel related malfunctions, lead to numerous accidents all over the world. Sometimes these accidents lead only to economical losses in form of material damage and delay while at worst they increase the number of road fatalities.

Had the driver more information of the status of the wheels, many of these damages could be avoided. For instance, detecting a sound suggesting that a tyre tread is about to break loose or alerting the driver about a locking brake before further damage will have occurred will result in immediate improvement of road safety.

For these goals, Acoustic Tyre Monitoring System (ATMOS) monitors the sound of each wheel or set of wheels while the vehicle is on road, providing processed real-time information in form of warning signals and recommendations to the driver as an integral part of Advanced Driver Assistance Systems (ADAS).

As this development work is multi-disciplined, it is realized by a development partnership consisting of small- and medium-sized companies. The key partners represent following areas of expertise:

- Automotive applications and traffic security
- Digital signal processing
- Adaptive and learning systems, data mining
- Electronics productisation and production

On top of these parties, the project involves a tyre manufacturer, trucking company, bus operator and national truck association, who offer their services in form of e.g. testing facilities.

DESCRIPTION OF THE SYSTEM

ATMOS system and development project consists of several challenging sub-projects. First of all, a front-end unit is to be designed for use in demanding use conditions in the undercarriage of the vehicle. Second, a central unit is to be designed, or alternatively the system is to be integrated to interface with an existing embedded data system of the vehicle.

In addition to the hardware units, two major software programs are to be programmed: The third challenge is the signal processing algorithm detecting anomalies in the sound emerging from the tyres and wheels, while the fourth challenge is the user interface program to be created with reliable and adaptive decision-making algorithm. In regard of the operating of the system, success in software development is of greatest importance, when compared to hardware system. The operation of the system is illustrated in Figure 1.

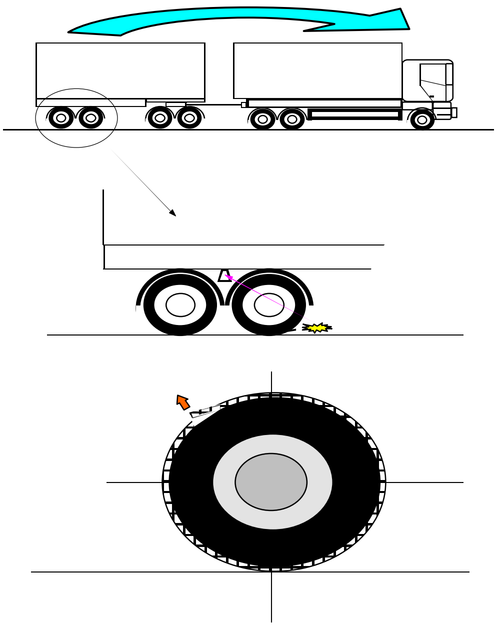

Figure1. Simplified illustration of the principle of Acoustic Tyre Monitoring System.

Hardware

From the application point-of-view, the most important piece of hardware is the electronics front-end attached close to each set of wheels in the undercarriage in Figure 2. This weather-proof and robust case includes a microphone for recording ambient sounds, analog-to-digital converter to transform the microphone signal into digital format, and digital signal processor for analysing the microphone signal, representing the sound data.

When anomalies are detected in the incoming sound data, appropriate information is sent to a central unit, being either a dedicated unit residing in the cabin or the embedded data system of the vehicle. Based on this information and – if applicable for the message in question - after comparing the information to the data available from the other front end units, the central unit will give appropriate warning messages to the driver.

Pre-processing the data locally is justifiable for several reasons. First of all, it allows use of cost-efficient signal processors, sufficient for processing the signal of one microphone. Secondly, analysing the data locally greatly reduces the amount of data to be transmitted between the front-end units and the main unit. Third, low amount of data traffic allows a variety of data transmission methods to be available as options: existing data buses; dedicated low-bandwidth cabling; or wireless data transfer.

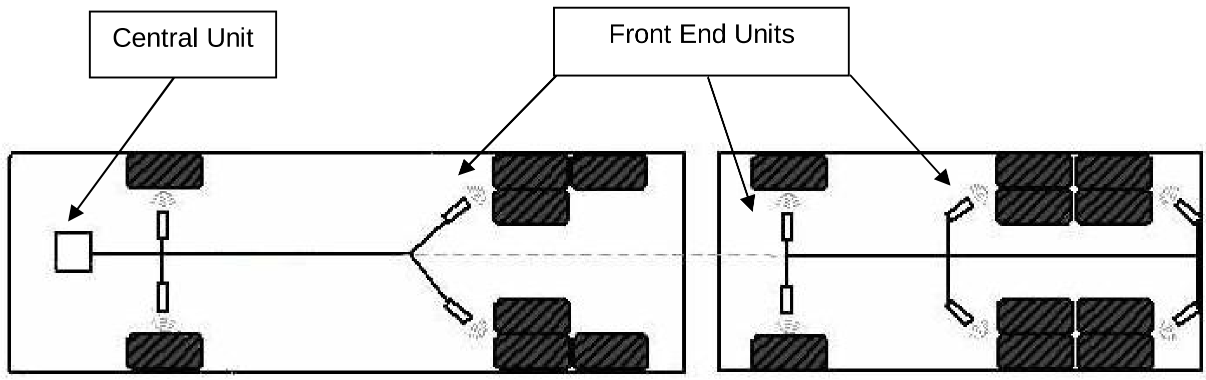

Figure 2. Layout of ATMOS system in vehicle

Depending on the actual application the hardware configuration may naturally be changed. The key elements are to be preserved, though: the signals of multiple microphones representing the data of various wheels are first digitalized and then are processed in a signal processor in real time. The signals are analysed both individually as well as by comparing them with each other.

Software Algorithm

Detecting tyre and wheel malfunctions by monitoring their sound is by no means a trivial task. Nevertheless, development in signal processing technology allows use of techniques formerly unavailable for applications such as this. Principally similar signal processing techniques are also applied e.g. in image processing when monitoring driver alertness.

One of the key issues in algorithm development is adaptiveness to different weather conditions, road surfaces and speed, not to mention tyres themselves (1). This calls for an extensive amount of measurement data, i.e. sound files from various situations, forming the basis for the algorithm development.

The algorithm development was first started with sounds recorded from tyres in various states in laboratory conditions, and the initial algorithm developed to differentiate between a good tyre and a bad tyre. After this, a more covering set of sample sounds was created in laboratory conditions to differentiate the stages of damage in tyres, and recordings on real vehicles were started.

Real-life data are gathered with the assistance of transportation companies today. Recording equipments are assembled to a number of trucks and buses which provide a good basis for algorithm development and field testing. These sound samples consist of practically any weather and road conditions and they are utilized to increase the robustness of the system.

Initial goal is to detect a loosening of tread in the earliest possible stage. Ultimately, development targets include e.g. the following:

- Tread separation
- Wheel bolt loosing
- Locked wheel
- Loss of tyre pressure
- Brake pressure tube leak
- Wheel bearing malfunction
- Hidden, internal damages of tyre carcass
- Loose particles stacked in the tread

The decision function at ATMOS algorithm is based on probability of defection. Different types of defections in a tyre require a various detection mechanisms (2). When the comparison algorithm detects a change which does not fit in decision boundaries, an alarm signal will be given for parallel signal processing detection algorithms and the probability of defection increases temporarily.

These changes are most frequently occasional by nature and the total detection algorithm chain is not necessary to complete layer by layer. In the case of unnecessary suspection of tyre defection ATMOS will return to its previous state at monitoring and difference spectrum comparing.

Besides, ATMOS algorithm uses periodical phenomena as an advantage effectively. The method is based on time-domain effect of frequency bumping, which is directly related to the speed of a vehicle and to the rotation frequency of a tyre. Time domain signal is divided into *n* segments and a Welch averaged periodogram is estimated from every time segment. The average of powers at every frequency component at the estimate of each segment is calculated and saved to a short-time buffer. The difference of these time-ordered average estimate levels at the buffer is calculated to generate a difference signal:

$diff(x) = ave(x+1) - ave(x)\ ,\ x = [0, 1, 2, \ldots , n-1]$

The length of a segment *n varies* with the speed to reveal periodical phenomena in a similar way as a parameter for the time segment length would have been triggered at every tyre revolution.

Figures 3 and 4 show the frequency bumping effect in case of impulsive signals of loose bolts, when time segment lengths are correctly calculated to match the rotation speed of a tyre.

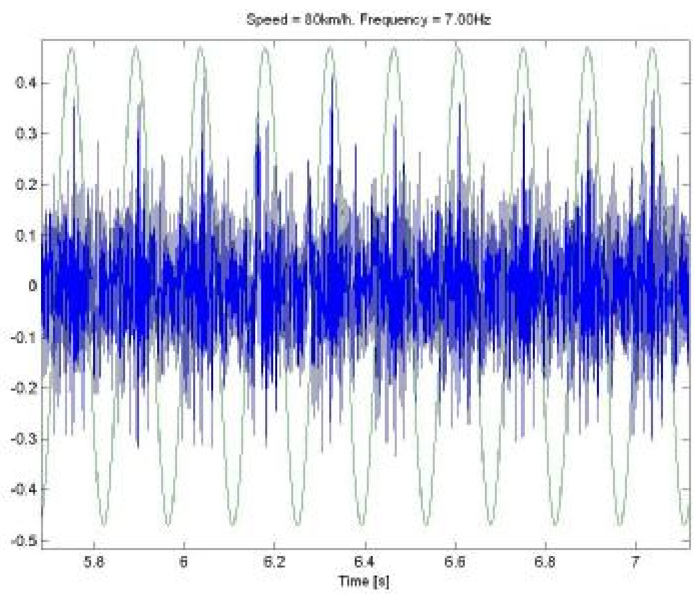

Figure 3. Time domain signal and 80 km/h speed matching sine signal of the same tyre

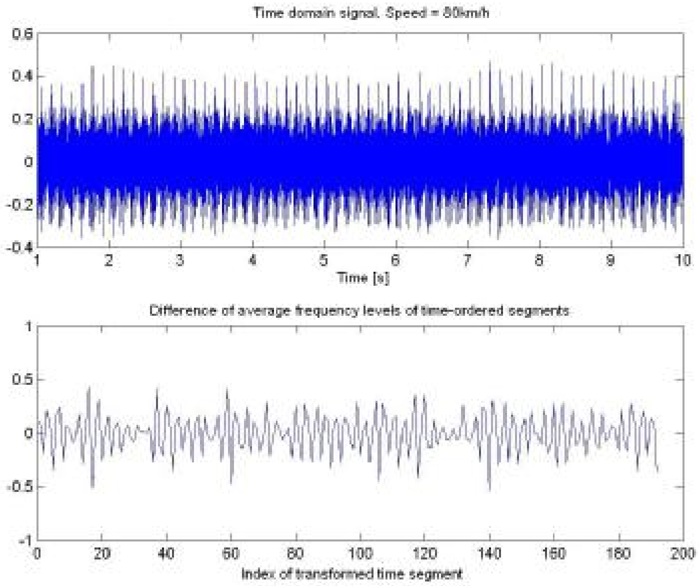

Figure 4. Difference signal of averaged, time-ordered spectra of time segments suited to the speed of 80km/h

Shell Software

Shell software, when understood broadly, includes both the user interface and the software operating under it, including the coordination software for monitoring several front-end units, as well as decision-making algorithm for comparing sound data received from them and alarming the driver accordingly.

The practice of comparing data recorded on different locations of the vehicle is an important concept in our context, as many of the changes in the sound monitored result from natural and normal conditions. These include speed change differences, road surface differences and other traffic. Being able to compare the data from several monitoring front-end units considerably reduces the likelihood of false alarms; if similar changes are observed in all units or e.g. all units on the left or right side of the vehicle, they are most likely changes in operating conditions, not in tyre or wheel condition.

This also suggests towards the adaptiveness of the system. The anomalies in sound have to be picked up and detected from the sound data with the base sound varying greatly (3). Furthermore, false alarms should be non-existent, as otherwise the system will unavoidably be deemed useless by the operators – the drivers. Adaptiveness to various operating conditions and learning the sound spectrum of individual tyres and the effect of their aging is hence built into the system and decision-making algorithm.

Conceptually, the user interface, or shell, program can be run in a dedicated processing unit or it can also be integrated to be a part of an embedded computer system already designed in. After all, by its nature the ATMOS system can be seen as a part of the Advanced Driver Assistance System.

OPERATION OF THE SYSTEM & TEST RESULTS

As an example of the sound analysis to be used as a basis for decision-making, the spectrum of a tyre in good shape is presented in Figure 5. The spectrum shown is calculated using an averaged modified periodogram method which increases the reliability of the spectrum estimation (4).

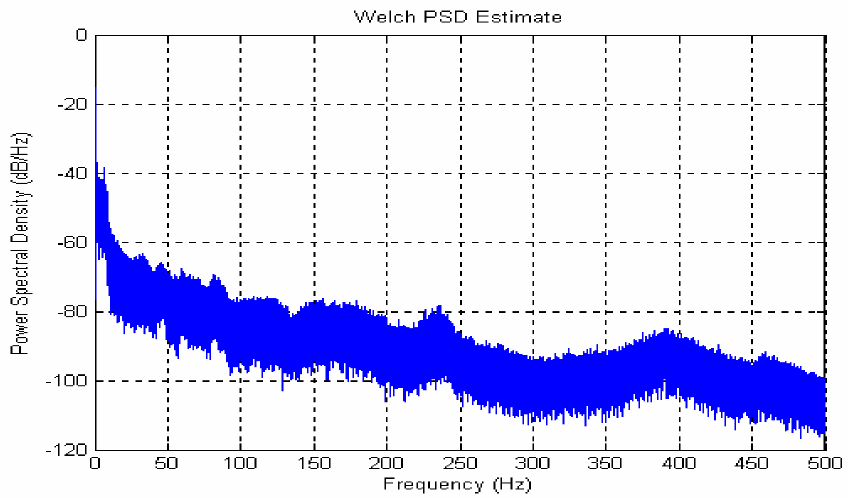

Figure 5: Spectral power density distribution of a good tire

The similar analysis done on an individual, defected tire yields in the spectrum presented in Figure 6. It can easily be seen that the power density distribution in 200-250 Hz region is substantially different, suggesting a malfunction. In the succeeding decision-making algorithm certain malfunctions are so obvious – such as a separated tread or a locked brake - that they can be detected from the signal itself. For other signals as well as for ruling out the environmental elements and other parameters such as speed, the results are compared with each other. Possible comparing method e.g. in the above case may be deduction of spectral density of power of tire noise. According to the difference, the defect probability value is defined for the decision-making algorithm.

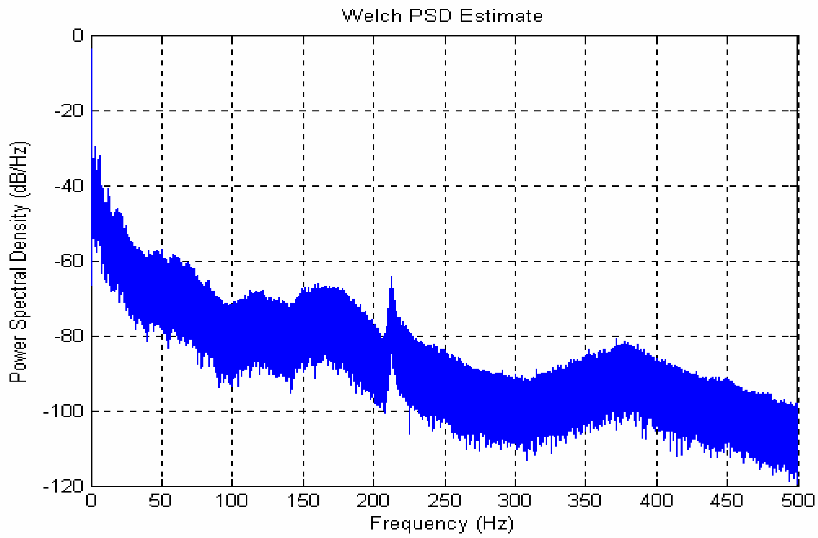

Figure 6: Spectral power density distribution of a defected tire

DISCUSSION

Monitoring the sound of tyre and wheel malfunctions with digital signal processing technology as the primary method for analysis is a relatively new approach to the problem at hand, not least because of the short history of digital signal processing as a technology. The challenge is by no means trivial, but as it is technical by nature it is therefore solvable with adequate resources. Similarly, the identification of the informative parameters in the sound spectrum and finding their usability in the statistical adaptive learning process in the shell program presents a major data-analytical challenge. Both of these challenges are being tackled using modern but extremely efficient computational tools new in the field.

Whether the solution will eventually prove to be beneficial enough to gain popularity as an after-market product or as a standard part of ADAS systems remains to be seen. A recent market analysis clearly showed that there is a market for both types of products. Hence, key drivers for success of ATMOS system are its ability to reliably predict and detect a fair number of various crucial malfunctions of the vehicle and to deliver this information to the driver, who can be dependent on the system improving his own safety, his cargo's safety and the roads in general.

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