INVESTIGACIÓN SOBRE LA APLICABILIDAD Y DESARROLLO DE SISTEMAS DE MEDICIÓN DE VELOCIDAD EN LA RUEDA

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FACULTY OF ENGINEERING
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Practice to obtain the title of
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Ing. JIMMY TOMBE ANDRADE

Director

Santiago de Calí, 16 de enero del 2006

Quiero dedicar este trabajo, primero que todo a Dios por estar a mi lado en cada paso de mi vida, por escucharme y por todas sus Bendiciones con las que ha llenado mi vida de personas demasiado especiales, de alegrías y del apoyo necesario para superar los momentos difíciles. ¡¡¡¡GRACIAS SEÑOR!!!!

Muchas gracias a mis padres que me han apoyado SIEMPRE y me han dado todo su cariño, dedico este trabajo y mi carrera a ustedes, papá y mamá. A mis hermanos, a mis tíos y a mis primas, muchas gracias por su enorme ayuda y por toda sus atenciones para conmigo, son muy especiales e importantes en mi vida. A mi abuela que ahora está con Dios, le dedico este y todos los logros que he tenido en mi vida, porque gracias a ella aprendí muchas cosas que me han ayudado a superar muchos obstáculos y a obtener lo que quiero.

Igualmente dedico este trabajo a mis amigos y compañeros inseparables, gracias por su ayuda, compañerismo y por los buenos momentos, esta etapa no sería tan inolvidable sin ustedes.

A todos y cada uno de ustedes, gracias….

María de los Ángeles Serrano Sánchez

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¡¡¡¡ MUCHAS GRACIAS!!!!

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GLOSSARY

TPMS (TYRE PRESSURE MONITORING SYSTEM): system based on electronic circuits and algorithm processes to view and control the pressure level on a tyre.

SENSOR: electronic device used to register a physical parameter and indicate the variable's value for such parameter.

VELOCITY: variable that indicates how fast a body is moving.

WSS (WHEEL SPEED SIGNAL): signal taken from the wheel that indicates the velocity of such wheel.

MATLAB: software, based on mathematical process, used to develop the algorithm that was developed for this research.

FFT (FAST, DISCRETE, FOURIER TRANSFORM): is a discrete Fourier transform algorithm which reduces the number of computations needed for N points from 2N^2 to 2N lg N, where lg is the base-2 logarithm.

SOFTWARE: the programs, routines, and symbolic languages that control the functioning of the hardware and direct its operation.

SUMMARY

Scania CV AB with their group RESB - Chassis Control Systems is interested in a research and analysis of the potential in the wheel speed signals, and to determine if this kind of information can be used in the development of a passive tyre pressure monitoring system (TPMS).

The idea of a passive TPMS, is to use the wheel speed signals, generated by existing sensors, to monitor the pressure of the wheels, and exclude the use of extra sensors for this function.

This paper introduces a description of the work that has been done on the measurement and analysis of the wheel speed signals

INTRODUCTION

Safety is the most important issue in the production of any kind of product, especially in the production and performance of the vehicles of today. One very important tool to accomplish a safety performance of a vehicle is the Tyre Pressure Monitoring Systems (TPMS). TPMS are sophisticated features that can monitor, in many ways, the pressure in each tyre, in order to provide the driver important information to have a better control of his vehicle. By using the TPMS, the driver will always be informed if a tyre does not have the proper pressure level, for instance, when the tyre is deflating, this way the driver will be warned and safety precautions can be taken before any accident may occur. A good pressure control of the tyres can not only ensure safety but it can also reduce costs on fuel consumption and increase the lifetime of the tyres. For all of theses reasons TPMS are being installed in every new vehicle, as well as in many old ones. Basically there are two types of TPMS: direct and indirect, there is also a third type, hybrid, which is the combination of the original two.

A description of each type will be presented, to have a better understanding of the Tyre Pressure Monitoring Systems.

The work introduces the study of unfiltered wheel speed signals into their applicability on Tyre Pressure Monitoring Systems. The idea is to use the signal from the existing wheel speed sensors to identify if the pressure on each wheel is low or high. The wheel speed signals are generated by a sensor installed on each wheel, which consist of a toothed wheel that induces an AC voltage pulse in a coil. The frequency of the generated signal depends on the number of tooth per second that moves by the coil, or, in other words, how fast the wheel is turning.

1. JUSTIFICATION

The development of such investigation with solid theory and experimental bases, allows the beginning of a technologic development and advance for Scania, which leads to an evolution and improvement in the products that this company offers. This way, Scania could have the opportunity of giving better accommodations to their clients, like more security and control, taking, by these means, to each place where their technology goes, a better quality of life.

This investigation and development gives a great benefit to the world automobile industry. Due to the fact that Scania has production and assist points all around the globe, their applications spread rapidly taking the humanity towards a future with the highest technology implemented on trucks and busses.

With this investigation, not only it is achieve a development for the control of velocity, but it creates a base of knowledge and documentation, for the participants of the project and for the Scania team, and for other researchers and people interested on the subject, by which it may be achieve the improvement in other areas of the automobile systems, and also be used to continue with other investigations that could lead to much more advanced systems.

2. OBJECTIVES

2.1 GENERAL OBJECTIVE

- Elaborate a work that includes the analysis and simulation of signals, based on real measurements from the velocity signals from the wheel, and the collection of information form other departments of Scania (engine and gearbox development, etc) to create a map over the possibilities that the company could use to improve the performance of their vehicles, and this way grow and continue with a high position in the future automobile industry.

2.2 SPECIFIC OBJECTIVES

- Write a report that maps out the future possibilities for development in this area together with an estimation of the possible applications on our products (trucks and buses) and their benefits for our customers.

- Make the documentation of the design process for future improves and updates.

- Generate a series of reports of investigations and thesis recompilation from different universities in order to create documentation that could be used to expand the area of knowledge.

3. EXPOSITION OF THE PROBLEM

According to Fredrik Gustavsson (professor in sensor-information, University of Linköping, Sweden) access to unfiltered wheel speed information is one of the most important prerequisites for future development of functionality in the vehicle industry. Individual wheel speeds can, among other applications, be used for calibration of real speed, passive tyre pressure monitoring, friction estimation and optimization of automatic gear selection. Today, Scania do not have access to the unfiltered wheel speeds since these signals are gathered by the brake system that is controlled by the sub supplier.

The labour is to investigate the possible functionality Scania could develop if we had access to the individual, unfiltered wheel speeds. How could this information be used together with other information on the CAN-bus to enhance the performance of the complete vehicle? Which functions could be of interest for us in the future?

4. DESCRIPTION OF THE TYRE PRESSURE MONITORING SYSTEMS

4.1 DIRECT TYRE PRESSURE MONITORING SYSTEM

This type of system uses a pressure sensor mounted in each wheel, to measure the pressure and the temperature in each tyre and, in just a few milliseconds, gives this information to the driver. The temperature is monitor to compensate for the pressure variations that come from the heated driven wheels, or cold atmospheric temperature. The pressure data is received by a central unit, analyzed and shown on a display. The display tells the driver the actual pressure in each tyre and gives a warning if one or more tyres, and which of them, are under inflated.

Direct TPMS can detect small pressure losses; some of them can detect a pressure drop as small as 0.07 bar. Because of the individual sensors used, they are able to detect when any tyre is deflated or when any combinations of tyres are deflated in any pressure difference. Another advantage of this system is that it operates with battery and thus, they are also working when the vehicle is stationary.

For all of these advantages, of working with sensors and an independent power source, the direct, is the most reliable pressure monitoring system, but because of the use of these equipment, the direct, is the most expensive one. This is the reason why the Indirect TPMS was born and developed.

4.2 INDIRECT TYRE PRESSURE MONITORING SYSTEM

The indirect TPMS works with the wheel speed sensors used with the Anti-Lock Braking System of the vehicle. They are called indirect or virtual because the system does not use pressure sensors for the measurement, but the pressure information is calculated using the available data from the wheel speed sensors. By using pre-existing sensors, the cost of implementing this system are a lot lower than using the direct TPMS. And this is its best advantage.

A lot of research is being done on indirect TPMS, so far, two methods have been studied and developed to work with the wheel speed data. The simplest method, the *Wheel Radius Analysis*, is based on the fact that the tyre pressure affects the rolling radius of the tyre, and because of this the rotational speed is also affected. The main idea is to compare the speeds on each wheel by using a sum relation that should be close to zero if all of the tyres are equally large, it can be possible to monitor the pressure variation. The second method, the *Vibration Analysis*, is much more complex. It works with the tyre modelled as a vibrating spring-damper system, from which resonance frequency information can be extracted and used to analyze and indicate tyre pressure variations.

Both methods have disadvantages. The radius analysis is sensitive to variations of the speeds due to factors other than pressure loss, like when the vehicle is turning, or when accelerating or braking. And for example, the vibration analysis is sensitive to different road conditions. Many research and development projects are being done to improve this system and make it a more reliable tool for tyre pressure monitoring.

4.3 HYBRID TYRE PRESSURE MONITORING SYSTEM

A hybrid TPMS works with the advantages from the direct, the accuracy, and from the indirect, the cost savings. The pressure sensors monitor two tyres and the other two are monitored by comparing the wheel speeds and detecting a variation in their pressure.

5. INDIRECT TPMS USING WHEEL RADIUS ANALYSIS

The principle of this method, as previously mention, states that the rolling radius of the tyre decreases proportionally to the rate of deflation and consequently the wheel speed increases.

Many equations have been proposed to monitor the wheel speed changes correctly, avoiding erroneous alarms from factors other than pressure differences. Most current indirect TPMS, based on Radius Analysis, compares the sums of the wheel speeds on each diagonal:

$$ratio = \frac{(RF + LR) - (LF + RR)}{Average\_Speed}$$

Dividing the difference of the sums by the average of the four wheels speeds allows having a ratio that is independent of vehicle speed. If this ratio over passes a set tolerance, is because one or more tyres have a different pressure.

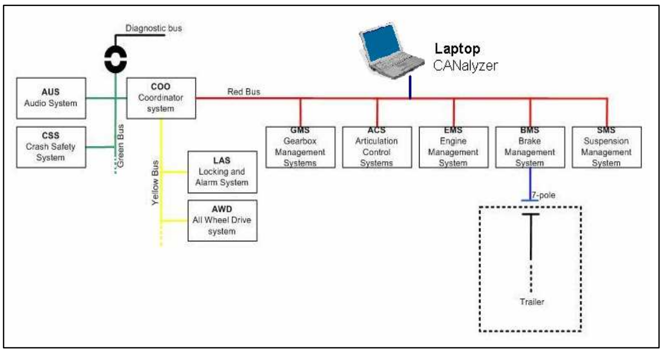
When comparing the wheel speeds it is important to take into account many factors that affect the speeds and do not come from a pressure variation. Turning, accelerating or braking produce a difference between the wheel speeds, therefore it is necessary to implement an algorithm that compensates for these variations.

5.1 MAKING THE MEASUREMENTS

To begin with the analysis some measurements were done using the truck Mormor. The WSS (Wheel Speed Signals) were taken from the CAN-bus, while the truck was running at different speeds, first with equal tyre pressures in all wheels, and then with a lower pressure in the front left tyre.

Using the software CANalyzer it was possible to save the WSS data sent by the EBS on the Red Bus.

Figure 1. Diagram of the connection between the Control Unit and the Laptop running the CANalyzer.



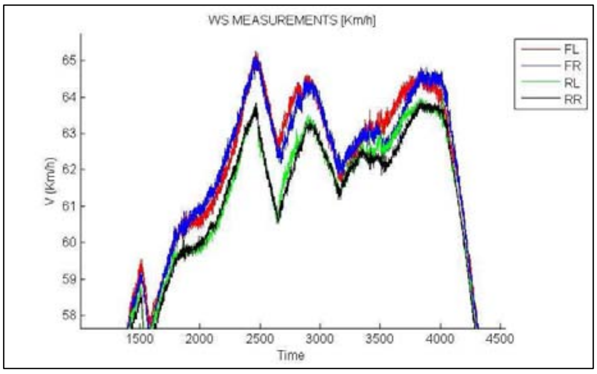
5.2 FILTERING AND CORRECTING THE WSS

A model in MatLab's Simulink was created to view, work and analyze the WSS information. For the initial part of the work, the measurements corresponding to equal tyre pressure in all wheels ware used. The following are the specifications of the test:

<u>Measurement Parameters</u>
Date: 4/11/2005
Truck: Mormor
Load: None
Hour: From 3 Pm to 5 Pm
SAMPLE 1:
Pressure of 8 bar in all tyres.

The next figure shows a graph of the speeds of the four wheels at the same tyre pressure.

Figure 2. Speed Signals from the four wheels, with equal tyre pressure of 8 bar.



To improve the signal, it was smoothed with a Lowpass Filter. The model of the implemented filter is the following:

$$y(n) = \frac{a}{b}x(n) - \frac{c}{b}y(n-1)$$

To calculate the new value the filter takes 10 % of the new input value and 90 % of the old output value:

$$\frac{a}{b} = 0.1 \qquad \frac{c}{b} = 0.9$$

The discrete filter block from Simulink was used, to model and apply the selected filter values to the signal.

$$H(z) = \frac{a}{b + c \cdot z^{-1}}$$

It was also necessary to take into consideration the physical imperfections of the wheels that come from manufacturing and use; as well as the small differences between each wheel of the truck. The wheels and their tyres are not exactly the same and they are not exactly equally made. They are all of the same kind and may have approximately the same pressure, and so they have the same size, weight, etc., but this is not precise.

The wheels may also be mounted on the axle at different heights from the ground, or may not be totally perpendicular to their axle, etc., and all of these errors cause a difference in their speed and therefore it could lead to a malfunction in the monitor algorithm. An attempt to correct these small physical errors has been done, and a correction factor has been calculated.

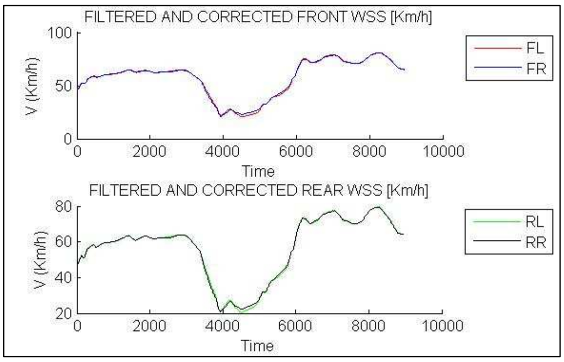
The quota value of the two front wheel speeds is, in reality, approximately 1 (which in a perfect case it should be exactly 1). To correct this error, as much as possible, and make the quota closer to 1, the quota is multiplied by a filtered correction factor; which can be calculated from the same wheel speeds.

$$\frac{w_1}{w_2} \approx 1 \quad \Rightarrow \quad \frac{w_1}{w_2} * \frac{1}{k_{12}} = 1 \quad \Rightarrow \quad k_{12} = \frac{w_1}{w_2}$$

$$\frac{w_3}{w_4} \approx 1 \quad \Rightarrow \quad \frac{w_3}{w_4} * \frac{1}{k_{34}} = 1 \quad \Rightarrow \quad k_{34} = \frac{w_3}{w_4}$$

By comparing the front wheels and the rear wheels separately, it is possible to avoid erroneous pressure change indications generated by accelerating or braking.

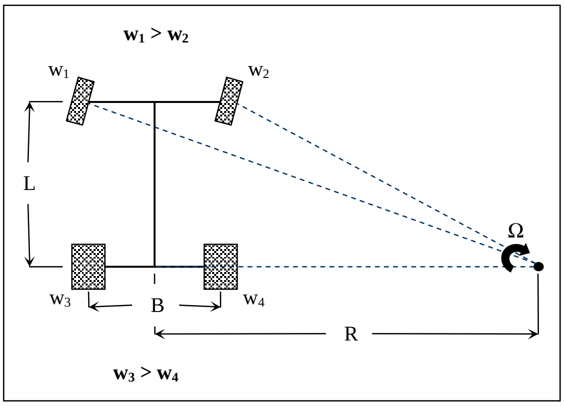
Figure 3. Wheels Speed Signals after been filtered and then multiplied by their corresponding correcting factors (k_{12} and k_{34}).



5.3 COMPENSATING FOR THE TURNS

The most important factor to correct is the difference in the wheel speeds during cornering or turning. When turning right, for example, the outer wheels, the front and rear left have a higher speed than the inner wheels, the front and rear right, since the first two have to cover more distance than other two, in the same amount of time.

Figure 4. Geometric model of the truck when turning right.



From the model it is possible to define the speed for each wheel as the following:

$$w_1 = \Omega\sqrt{\left(R + \frac{B}{2}\right)^2 + L^2} \qquad \text{(eq1)}$$

$$w_2 = \Omega\sqrt{\left(R - \frac{B}{2}\right)^2 + L^2} \qquad \text{(eq2)}$$

$$w_3 = \Omega\left(R + \frac{B}{2}\right) \qquad \text{(eq3)}$$

$$w_4 = \Omega\left(R - \frac{B}{2}\right) \qquad \text{(eq4)}$$

Where Ω is the angular velocity, R is the rotational radius of the rear axle of the truck, L is the distance between the front and rear axle, and B is the length of the rear axle.

Using the same principle as before for calculating a correcting factor, the turning-compensating value for the front wheels can be expressed as:

$$K_{turn} = \frac{w_1}{w_2} = \frac{\sqrt{\left(R + \frac{B}{2}\right)^2 + L^2}}{\sqrt{\left(R - \frac{B}{2}\right)^2 + L^2}}$$

(From eq1 and eq2)

The rotational radius R is calculated from the rear wheel speeds (eq3 and eq4) using the following definition:

$$R = \left(\frac{w_3 + w_4}{w_3 - w_4} \right) * \frac{B}{2}$$

Once the turning-compensation value has been calculated, it is applied to the WSS from the front wheels, and the speed differences that come from turning are reduced to about 39%. The next two figures show the WSS after they have been turning-compensated and the reduction of the turning factor, making the quota value closer to 1.

Figure 5. WSS from the front wheels after been compensated for the turning factor.

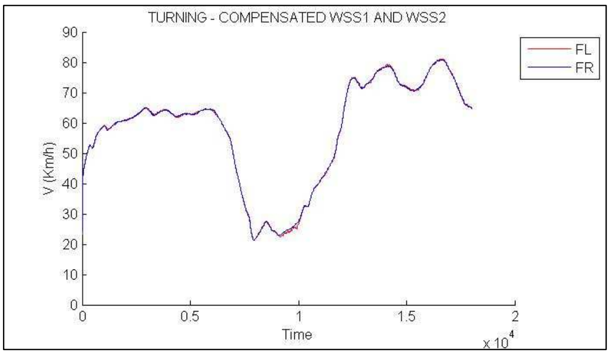
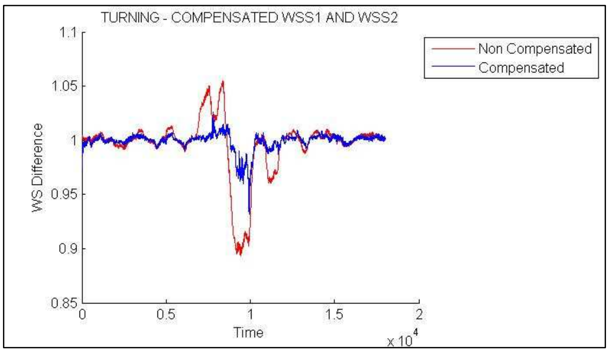


Figure 6. Comparison between the original speed differences (quota value), in the front wheels, and the speed differences after being compensated for the turning factor.



An extra compensation factor was calculated, to improve the performance of the turning-compensation phase. Since the wheel speed difference between the front wheels it is still considerable big, it was found that multiplying the rotational radius by an extra compensation value helps the turning-compensating factor to correct better the signal.

The error obtained after the turning-compensation phase was defined as:

$$e(n) = \frac{w_1(n)}{w_2(n)} - 1$$

An extra compensation value can be defined as:

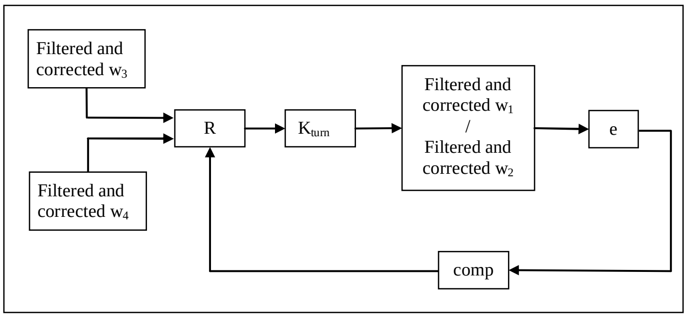
$$comp(n) = comp(n-1) + 0.001 \cdot e(n)$$

Then to improve the turning-compensation response, the error is calculated for each present wheel speed value and fed into an extra compensation value which is multiplied with the rotational radius and varies its value in a very small percentage to adjust the turning-compensating factor; in order to reduce the error with each interaction.

$$R = \left(\left(\frac{w_3 + w_4}{w_3 - w_4} \right) * \frac{B}{2} \right) * comp$$

A model to explain better this compensation phase of the algorithm is shown in figure 7.

Figure 7. Model of the Turning-Compensation phase.



5.4 THEME CONCLUSIONS

The wheel speed signal has not been completely corrected and the compensation process is not totally successful. More correction should be performed, like filtering the last result that was obtained after all the processes, before it is possible to move to an evaluation phase that would lead to a more reliable result.

Even though the quota is not so close to one, there has been found a small difference between the mean error when all tyres have a pressure of 8 bar, and the mean error when the pressure of the front left tyre is lowered to 6.2 bar (error difference~0.004).

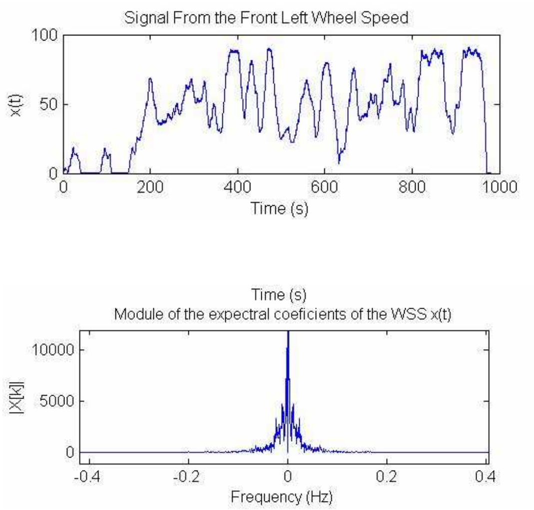
6. INDIRECT TPMS USING FREQUENCY ANALYSIS

6.1 WSS MEASUREMENT WITH CANALYZER

For the first attempt on obtaining the WSS (Wheel Speed Signals) the team intersected the data sent through the CAN-bus of a truck, which was running at different speeds.

Using the software CANalyzer it was possible to save the WSS data sent by the EBS on the Red Bus. The WSS of the front left wheel was then represented in a time and in a frequency plot. The frequency information from the WSS was obtained using the Discrete Fourier transform, the *fft function* from MatLab.

Figure 8. Top: WSS from the front left wheel in a time plot. Bottom: Zoomed, WSS after a Discrete Fourier transformation.



As the graph shows, there is no important resonance frequency found. The frequency generated around 0 is a concentration of energy due to amplitude disturbance. The problem with this measurement was the sampling frequency. In a common car tyre the resonance frequency that gives the information of the pressure difference is found between 40-50 Hz. The average pressure in a car tyre is 2.3 bar, while the pressure in a truck tyre is 8.5 bar. According to the theory and previous investigations on TPMS, the vibration frequency is increased when the tyre inflation pressure is increased; therefore the resonance frequency needed for the analysis is much higher than 50 Hz.

The speed information from the front left wheel was sent through the Red Bus every 0.02s, which gives a sampling frequency of 50 Hz. According to the Nyquist Theorem, the sampling frequency must be at least 2 times greater than the frequency needed or measured (*2f*).

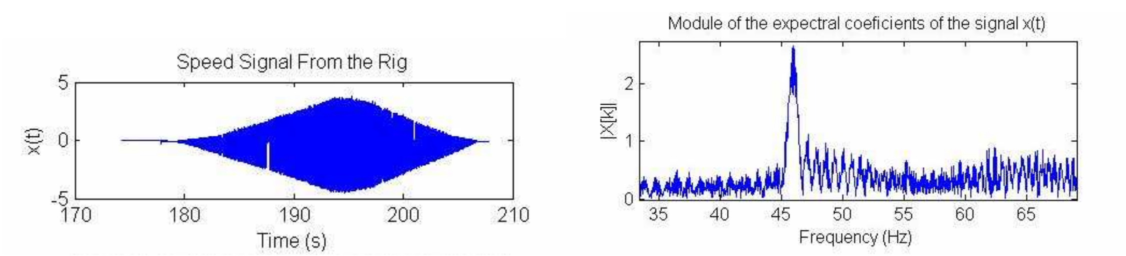
As a result, this first attempt on measuring the WSS and finding the resonance frequency for the pressure indication, ended in an aliasing effect, a creation of false images of the signal at frequencies below *f*.

(Results by using the m-file: FFTonFirstTest_Truck)

6.2 SPEED SIGNAL MEASUREMENT ON A RIG USING DIADEM

The second attempt was measuring the speed on a Rig by using the software Diadem. This time the sampling frequency was 500 Hz. The same process of transforming the signal information to the frequency domain, using the *fft function*, was done.

Figure 9. Top: Speed signal (from 0 to 90 to 0 km/h) from the Rig in a time plot. Bottom: Zoomed, Speed Signal after a Discrete Fourier transformation.



The graph shows a resonance frequency around 46 Hz, which could be spectrum information concerning the speed of the rig.

The aliasing effect appears one again. This sample frequency of 500 Hz can only be used to sample speed signals under 12.5 m/s. The maximum speed of a truck is 25 m/s (90 km/h), the radius of a truck wheel is 0.52 m aprox.; with this values the maximum angular speed is 47.86 rad/s.

If the angular velocity is also defined as:

$$\omega = 2\pi f$$
$$f = \frac{\omega}{2\pi} = 7.61\frac{rev}{s}$$

The number of teeth in the Rig is 100. So the relation follows:

⟶	1 rev/s	100 pulses/s
⟶	7.61 rev/s	761 pulses/s

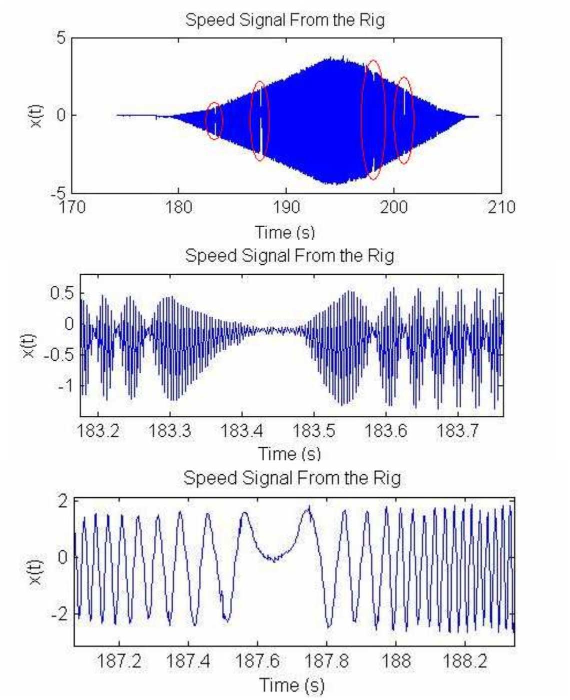
The frequency is defined as:

$$f = \frac{1}{T}$$
$$T = \frac{1}{761} \approx 0.0013\text{s}$$

Each tooth generates a pulse every 0.0013 seconds, so then its frequency is defined to be 761 cycles per second, or 761 Hz. This is the maximum frequency that is sampled and consequently the sampling frequency must be at least 1522 Hz.

This sampling frequency problem explains the appearance of some errors in the speed measurements. With the sampling frequency used it was only possible to sample low speed and when the speed on the Rig was increased, there is a “braking point” in the signal and then continues with some very wrong speed measurements. These inconsistencies occur in four points of the sampled data, and two of the first points are shown next.

Figure 10. First: Speed signal from the Rig with the four inconsistencies marked with red ovals. Second: Zoom at the first inconsistency observed. Third: Zoom at the second inconsistency observed.



(Results by using the m-file: FFTonSecondTest_RIG)

6.3 SPEED SIGNAL MEASUREMENT ON A RIG USING THE ROADRUNNER

Due to the limitations of the equipment used in the past measuring tests, it was necessary to work with a more power full instrument, like the ROADRUNNER produced by Skalar Instruments. Using the software Nemo and configuring to sample at a frequency of 5000

Hz, it was possible to obtain a correct speed signal from the Rig and then transform it into a frequency domain.

Figure 11. Top: Speed signal from the Rig (from 0 to 90 to 0 km/h). Bottom: Zoomed, Speed Signal after a Discrete Fourier transformation.

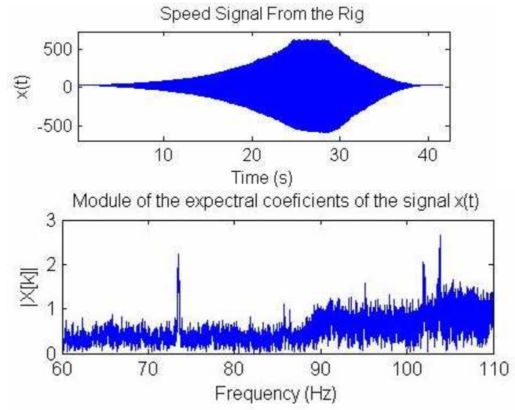
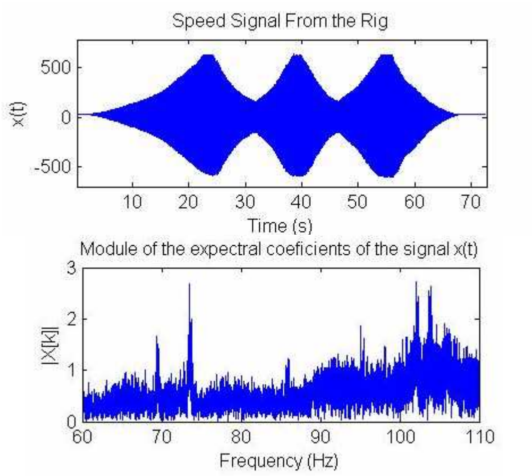


Figure 12. Top: Speed signal from the Rig (from 0 to 90 to 50 to 90 to 50 to 90 to 0 km/h). Bottom: Zoomed, Speed Signal after a Discrete Fourier transformation.



(Results by using the m-file: FFTonThirdTest_RIG)

6.4 WSS MEASUREMENT USING THE ROADRUNNER

In order to have more realistic measurements to obtain better results for the needed frequency analysis, the truck MAUD was ridden and different samples were taken using the Roadrunner, at a sampling frequency of 5000 Hz.

Different samples, with different wheel pressures were taken; all from the two front (non-driven) wheels.

Two of the different samples were used for the frequency analysis. The following are the specifications of the tests:

<u>Measurement Parameters</u>
Date: 4/10/2005
Truck: Maud
Load: None
Tyre Reference Number: 315/80r22,5
Wheel Radius Aprox.= 0.5223 M
Hour: From 3 Pm to 4:30 Pm

SAMPLE 1:

- Initial Tyre Pressures (Normal Wheel Temperature Conditions):
  Front Left Wheel: 8 bar
  Front Right Wheel: 8 bar

- Final Tyre Pressures (Warm Wheel Temperature Conditions):
  Front Left Wheel: 8 .4 bar
  Front Right Wheel: 8 .4 bar

SAMPLE 6:

- o Initial Tyre Pressures (Warm Wheel Temperature Conditions):

  Front Left Wheel: 6.2 bar

  Front Right Wheel: 8.4 bar

- o Final Tyre Pressures (Warm Wheel Temperature Conditions):

  Front Left Wheel: 6.4 bar

  Front Right Wheel: 8 .5 bar

The WSS used for the next analysis were taken from the Front Left Wheel of the First and Sixth samples made on the mentioned date.

To find the different resonance frequencies that correspond to different tyre pressures, five seconds were taken from each signal. Theses seconds had to match, a good as possible, a similar speed and estimate that these samples, both correspond to the same part of the road travelled. These, in order to guarantee that the only mayor difference between the two samples is the pressure in the front left tyre, and therefore the difference that could be seen between the two frequency spectrum graphs would be indicating a difference in tyre pressure.

Figure 13. Top: Five seconds of WSS from the front left wheel at a pressure of 8 bar. Bottom: Five seconds of WSS from the front left wheel at a pressure of 6.2 bar.

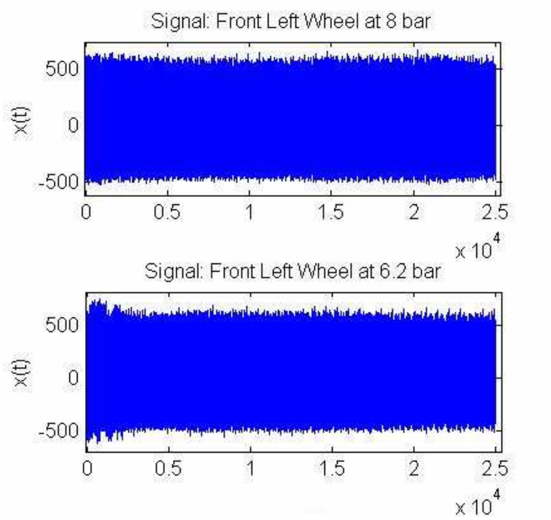


Figure 14. Calculated Speeds for the same front left wheel, from two different samples with different pressures.

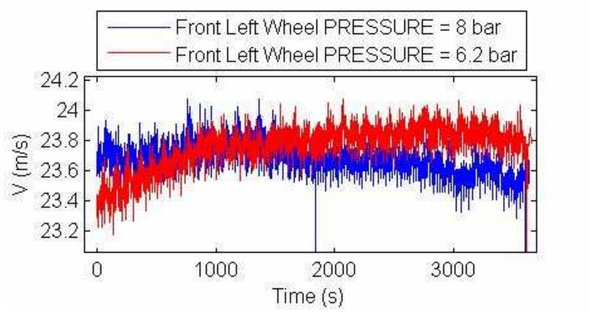
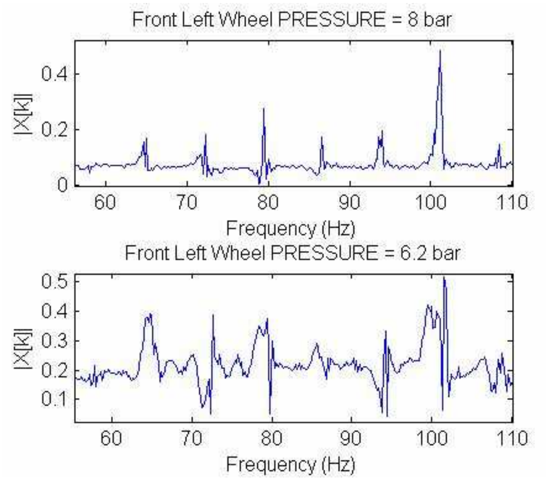


Figure 15. Zoomed, Module of the spectra coefficients of the WSS x(t) at 8 bar and at 6.2 bar.



The large peaks that are seen in the graphs are due to the imperfections in the toothed wheel. If the velocity would be less constant, the peaks would be blurred out by leakage effects. No resonance peaks that could indicate pressure difference can be seen between the two spectra plots, this interesting information is much possibly damage and buried inside the time disturbance cause by the toothed wheel.

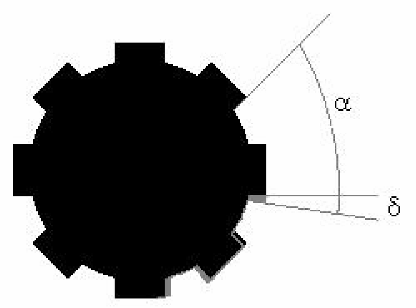
But there are still some other relevant differences between the graphs, for example, the magnitude of the signal. Perhaps it would be possible to use the variance and the mean of the frequency content to detect low pressure instead?

(Results by using the m-file: FFTonFLW8_6bar)

6.5 CALIBRATION OF THE TOOTHED WHEEL

As a result of the previous test analysis, it is now necessary to eliminate the time disturbance from the signal in order to find the needed frequency information for the tyre pressure indication. To eliminate this disturbance it is necessary to identify the errors in the toothed wheel. The toothed wheel is not perfect, it has angular errors from the manufacturing and aging, and these errors are registered when sampling and show up in the frequency content of the speed signal.

Figure 16. Toothed wheel with non-equal angular displacements between each teeth.



A way to improve the quality of the sampled signal, correcting the time disturbance, is to find the magnitude of the angular errors in the toothed wheel. Since the toothed wheel is always exposed to wear and tear, the identification algorithm must be recursive.

A linear regression model for the toothed wheel is:

$$y[k] = \omega \cdot (t_k - t_{k-1}) - \frac{2\pi}{L}$$

Where ω is the angular velocity of the wheel and L is the number of teeth in the toothed wheel. Here the measurement is based on the mean velocity over one revolution of the wheel, and the deviation from the mean level is modelled as tooth offsets.

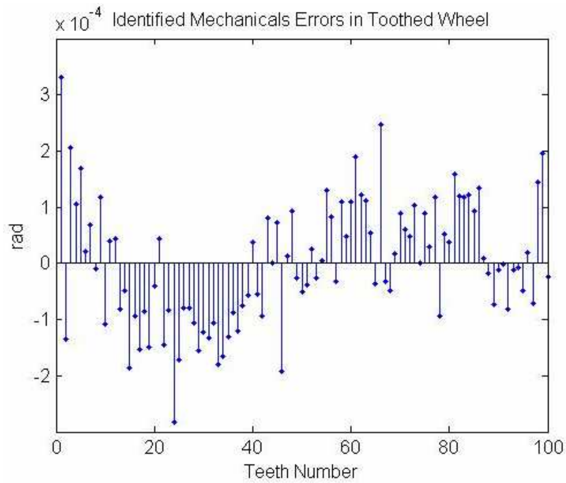
Using the previous equation it was possible to identify and calculate the angular position errors in each teeth. The parameters for the sample used to calculate and plot these offsets were:

- Same sample 6 taken on the truck MAUD
- Front Left Wheel: Initial pressure = 6.2 Bar

- Front Left Wheel: Final pressure = 6.4 Bar
- Sampled time used = 10 seconds from the original signal
- Number of teeth = 100
- Angular velocity = 44.89 rad/s

Figure 17 shows the results from the calculations using the linear regression model and the identification of the mechanical errors in the front left toothed wheel of the truck MAUD.

Figure 17. Identified mechanical errors in the toothed wheel using the linear regression model.



To test how well the identification algorithm works, two different groups of data from the same sample were taken and their calculated errors were compared. For this test, the same 10 seconds of sample 6 used for the past calculation, and another 10 seconds were taken from a different section of the same sample 6 signal. To assure the same conditions of constant angular velocity for both sets of data, the speed was calculated and plotted.

Figure 18. Constant Speeds for the same front left wheel signal sample, for two different groups of data.

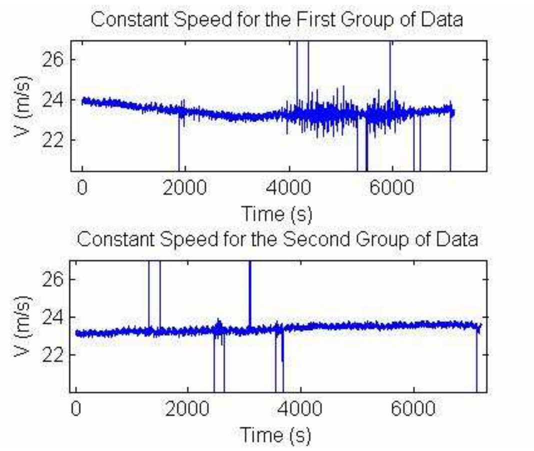
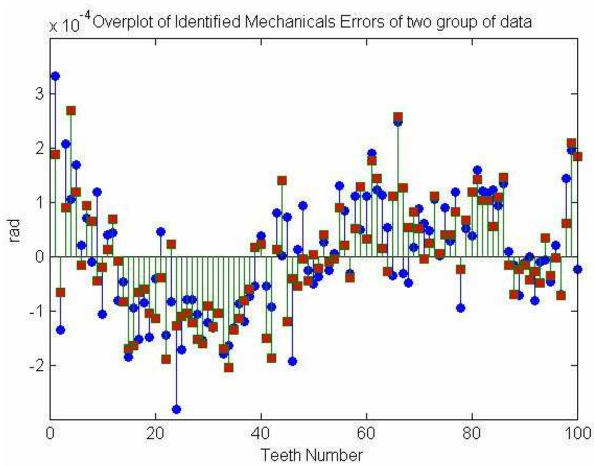


Figure 19 shows the comparison between the calculated offsets for the two sets of data. Since the first offset value calculated for one of the data is not necessarily the first offset value calculated for the other data, before doing the over-plot for the comparison, the best possible match was made, placing the error calculated for each teeth in the same position of the other calculated error for each same teeth.

Figure 19. Comparing the two sets of offsets.



(Results by using the m-file: calibrationTW)

6.6 THEME CONCLUSIONS

Even after solving the sampling frequency problems (Aliasing) in order to obtain the correct frequency transformation, no significant frequency resonance that may correspond to a pressure indication was found. The main reason could be that the correct filtering and cleaning of the signal could not be done successfully, because of the complexity of the problem and the shortage of time.

Another reason for not finding significant frequency information could possibly be due to the different physical characteristics of the truck's tyre, like thickness, high containing pressures, metal layer inside, and some other parameters that affect the modelled tyre as a vibration system. In other words, it could be possible that the resonance frequency for the pressure indication may be found in much higher frequency levels or that because of the physics of the tyre, the information should be treated different (Event Based Sampling) and examine much more carefully in order to not loose it within other disturbances.

7. CONCLUSIONS

The work developed led to many important results for the investigation. The study of the wheel speed signals is much more complex than expected but so far the outputs were satisfactory and of much importance for the research done.

This paper explains the entire process gone trough in order to analyze the measurements and experiments done for the study of the signals and their possible used in tyre pressure monitoring.

Finally, the present work is a very complete research of the mentioned subject and it represents an important source of recollection and information for the study of such theme and for other types of investigation regarding the wheel speed signals and their applicability in tyre pressure monitoring methods and systems.

8. RECOMMENDATIONS

- Present much attention in the measurement process, check for the right sample frequency in order to record all of the needed information, and avoid an aliasing problems.

- Carefully, verify the correct connection of all the equipment.

- Watch out with the possible noise that can appear in the measuring process, and use the appropriate cables for each connection.

- Remember to correctly configure the measuring equipment's software and any other device you may need for the experimental process.

- Be careful with the units you are working with.

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