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ABOUT USING THE VEHICLE VIBRATIONS FOR MEASURING ITS SPEED

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Abstract: The paper investigates the possibility of using the vibration signals of a vehicle to measure its speed. The principle of the method, the properties of the solution and some validation experimental results are presented. The method proves to be reliable, with a fair maximum error, but only works in some restrictive conditions: enough pavement excitation and a minimum speed of 20km/h. Fortunately, these conditions are satisfied by the system intended to use this method, which aims at diagnosing the pavement and the vehicle itself, while running at traffic speed.

Keywords: speed measurement, vibration sensors, crosscorrelation, vehicle, diagnosis.

1. INTRODUCTION

The speed of a vehicle is an important variable of its status, when thinking to diagnosis, to assisting the driver or to automatic driving. Different methods have been proposed to measure the speed of the vehicle. They include methods using internal sensors only (such as in odometry) and methods using external sensors. First class concerns the sensors attached to the wheels or other rotating parts of the vehicle. They give fair information about the speed, provided that the wheels do not slide on the road. They present some disadvantages: the speed value is not reliable when the vehicle is on skid and this information cannot be used for position estimation (speed integral), as the errors are integrated as well. The second class concerns the external sensors, such as radar, image processing devices, network of position sensors, GPS (Global Positioning System), differential GPS, etc. Many of them directly provide the position information, which is an advantage, as the speed simply can be derived from the position data. GPS provides a good approximation of the position, as long as the satellites are visible for the vehicle. However, the precision is not high (0.2 km/h) and the data are no longer available, when there is no visibility (for instance, in the tunnels). Better position information is provided by the networks of position sensors and by the differential GPS method. Both of them are associated with navigation in limited areas (for instance, indoor navigation or docking to marine platforms). Radar and image processing devices are also used for speed measurement, they provide a good approximation (see Czajewski, 2010), but they require a sensor on a ground position.

Another class of methods uses sensors inside the vehicle, which interact with the environment. These are mainly vibration, ultrasound or light sensors, who gather information from outside the vehicle. Some of them exploit the Doppler phenomenon, which reflects the relative speed of the vehicle and the environment. As an example, the *Laser surface velocimeter* sends a laser beam to the pavement and measures the speed through the frequency deviation of the reflected radiation. There are commercial products based on this method, whose error goes down to less than 0.1 km/h, such as the series presented by the company Polytec (***, Polytec, 2017). Other sensors provide signals reflecting the relative position of the vehicle and the environment, such as the ultrasound devices. They can measure the distance to an obstacle and the direction of this obstacle by exploiting the time of flight (TOF). This is the time necessary to the direct wave to reach the obstacle, plus the time necessary to the reflected wave to come back to the sensor. Because the reflected wave is subject to scatter, frequency deviation and other distorting phenomena, the TOF is measured by crosscorrelation between the reflected wave and a model of the emitted impulse train. This is the case of a method intended to be used for ships and described in US patent 3790926 (***, US patent, 1974).

This paper deals with a similar method, applied to the terrestrial vehicles and using the vibration signals, collected by cheap accelerometers. It mainly measures the speed through the delay between the vibration signals of the vehicle. The method itself is not original, the objective of the paper is to investigate the opportunity of using it on vehicles and the performance one can expect. Its advantages, drawbacks and limitations are examined through the following sections. The principle of the method and the properties of the solution are presented in sections 2 and 3. The experimental results are presented in section 4 and some conclusions are drawn in section 5.

2. THE MEASURING METHOD

This method assumes a set of vibration sensors deployed into a regular car or another vehicle. They provide vibration signals, including the vertical components of the vibrations, mainly produced by the interaction of the vehicle with the pavement. Such a sensor subsystem, based on cheap accelerometers, was described in the work of Chiculiţă and Frangu (2015). Figure 1 presents some possible positions of the sensors. For simplicity, we can suppose only two sensors, placed on the left (or right) side of the car body, one of them just on top of the front wheel damper, the other on top of the rear wheel damper.

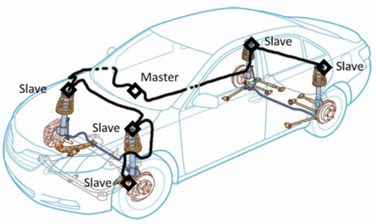

Fig.1. Positions of some sensing nodes and of the master node, from (Chiculiţă, 2015).

The signals provided by the sensors have many sources: vibrations produced by the interaction of the vehicle with the pavement, vibrations of the engine, transmitted through the car body, and the vibrations of the mechanical transmission (mainly from the gear to the wheels). For the beginning, we can assume the vehicle goes straight and the main source of vibration signals originates from the pavement, the other sources are considered of low power. Any deviation of the pavement from a smooth surface will be observed on both sensor signals. The delay between them depends on the speed and on the distance between the wheels. Accordingly, the speed of the vehicle is:

$$(1)\ v = L / D\,,$$

where L is the distance between the wheels (easy to measure for a specific vehicle) and D is the delay between the front and rear signals. This delay is not easy to measure, as the signals are not identical and contain considerable measuring noise. The best way to find it is to use the crosscorrelation function of the two signals. If they are denoted by $x(t)$ and $y(t)$, the crosscorrelation function is:

$$(2)\ R_{xy}(\tau) = E[\,x(k)\cdot y(k+\tau)\,]\,.$$

This is the statistical mean (or the expected value) of the product between a signal and the delayed version of the other signal, if the value of the delay is denoted by the variable τ. The signals provided by the sensors are sampled (discrete time) and their processing concerns short sequences only (for time response reasons). Accordingly, the discrete version of the crosscorrelation function is (Huang *et. al.*, 2006):

$$(3)\ R_{xy}(\tau) = \begin{cases} \dfrac{1}{n}\sum\limits_{k=0}^{n-1} x(t+k)\cdot y(t+k+\tau), & \tau \ge 0 \\ R_{yx}(-\tau), & \tau < 0 \end{cases},$$

where n is the length of the analyzed sequence, expressed in number of samples. Let us assume the two discrete-time signals are given by the relations:

$$(4)\ x(k) = a_1 \cdot s(k) + z_1(k)$$
$$(5)\ y(k) = a_2 \cdot s(k-D) + z_2(k)\,,$$

where $s(k)$ is the original signal produced by the interaction with the pavement, D is the delay, $z(k)$ are the noise components of the sensor signals and a are the coefficients reflecting the different gains of the wheel-damper-sensor chains. The function in eq. (3) becomes (Huang *et. al.*, 2006):

$$R_{xy}(\tau) = a_1 a_2 R_{ss}(\tau - D) + a_1 R_{sz_2}(\tau) + a_2 R_{sz_1}(\tau - D) + R_{z_1 z_2}(\tau) \quad (6)$$

If the noise components are small enough, the first term in eq. (6) is the dominant term. It is the autocorrelation function of the original signal, $s(k)$, which has a maximum for the value 0 of the argument. It follows that the maximum of the crosscorrelation function appears for the value of the argument τ (Huang *et. al*., 2006):

$$\tau = D. \quad (7)$$

The relation (7) shows the method to find the delay D: take the crosscorrelation function of the front and rear signals, then take the value of the argument of the maximum of this function. Assuming the vehicle travels forward, the delay will always have the same sign. If it switches to the opposite sense of movement, the sign of D will switch too. Figures 2 and 3 present two signal records and their crosscorrelation function. The length of the recorded sequences is 1024 samples and the length of their crosscorrelation function is 2047 samples, where $\tau = 0$ corresponds to sample index 1024. The maximum of the function in figure 3 is located at the value 1038 of the argument, which means the delay is D=14 samples.

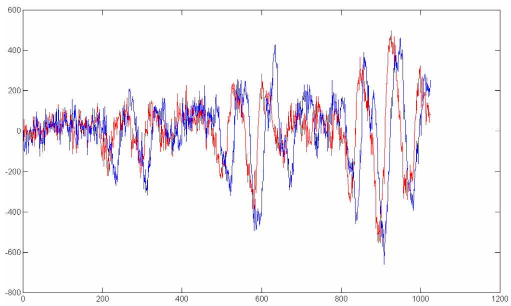

Fig.2. Recorded vibration signals.

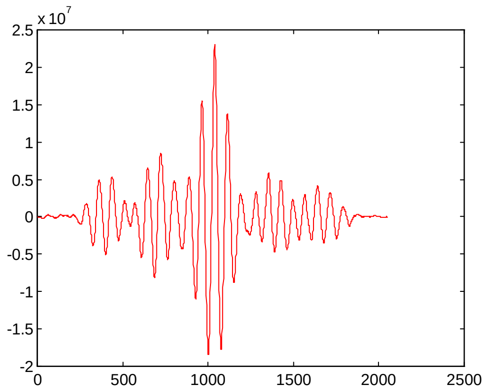

Fig.3. Crosscorrelation function of the vibration signals.

3. THE PROPERTIES OF THE SOLUTION

This section is dedicated to the implementation details and to the limitations of the method. First of all, it should be stated that this method does not provide more accuracy, with respect to other methods, nor does it eliminate the need of the classical speed measuring system. Instead, it is useful for the diagnosis of the vehicle where the vibration measurement system was already installed. It provides the speed information, together with the vibrations, without the need of collecting the speed data form other subsystems. The other speed measurement subsystems will be separately exploited for assisting the driver, for ABS, etc.

A preliminary observation concerns the filtering of the white noise. The crosscorrelation function has the property of reducing the contribution of the noise, as one can notice from relation (6). If the noise components are not correlated to the original signal $s(k)$, the last terms of this relation decrease to 0, when the length of the sequence increases. So, the next steps are to decide the length of the vibration sequences to be processed, and to examine the contents of the signals included in the noise, so far. Another preliminary observation concerns the values of the delay to be measured. A simple estimation leads to values between 80ms (speed of 120km/h) and 800ms (speed of 12km/h). We considered a distance of 2.6m between the wheels. Obviously, the delay increases for lower speed, but this is no longer interesting, at least for the diagnosis system, as the vibrations become insignificant at low speed.

The sequence length is an important implementation parameter. On one side, long sequences require long recording time, which delays the speed measurement. Obviously, a fast response time requires short sequences. On the other side, short sequences do not lead to noise filtering. There is another important inferior limitation of this length. In order to extract the delay between the signals, the length of the sequences should be larger than the delay, say twice. This means the minimum sequence should be of 160ms, for high speed, and 1.6s, for low speed. It is not a simple problem to decide the length as function of the speed, as long as the speed itself is the unknown variable, but this problem can be skipped for the moment. The main conclusion here concerns the length of the analyzed sequences, which should be at least twice the measured delay.

Now, coming back to the initial hypothesis, that the main component of the recorded signal is produced by the interaction between the wheels and the pavement: this not always true. In fact, the vibrations of the engine and of the transmission mechanism propagate through the car body and will contribute to the recorded signals. The extreme case one can imagine is the still vehicle, but with a running engine.

There is no vibration coming from the pavement, but there is a maximum of the crosscorrelation function, determined by the rotation speed of the engine shaft. There is no verified condition to decide when this maximum will point to the rotation speed, instead of the vehicle speed. We simply can assume that the excitation from the pavement should be larger than that of the engine, in order to avoid this kind of error. Fortunately, both situations are useful for the system exploiting the recorded vibrations, as we are equally interested in diagnosis of the engine, of the transmission and of the car suspension. Another problem raised by the propagation of the vibrations is the oscillatory behaviour of the suspension. The recorded vibration signals contain large components, in the spectral resonance band of the dampers. However, they do not produce errors, as we can assume the front and rear dampers having similar behaviour. On the contrary, these components can contribute to the diagnosis of the suspension system. If avoiding the suspension resonance is necessary, the sensors can be mounted on the low side of the damper, as one can see in figure 1, just near the front left wheel, but they will get a much larger value of the acceleration.

Assuming there is no rough error produced by the absence of pavement excitation, the maximum speed error should be evaluated.

One error source is the discrete nature of time: the delay can be a non integer number of samples. This problem can be simply solved by interpolation. The crosscorrelation function can be approximated by a polynomial, around its maximum, using 3, 5 or 7 neighbour samples. Then, the argument of the maximum is determined by analytical means.

However, if the integer value is used, the maximum deviation is 1/2 sample. A normal sampling period is 1ms (see Chiculiţă and Frangu, 2015), as the useful band of the acceleration sensors is 400Hz. This means the maximum relative truncation error is 0.5ms/80ms (for the highest speed).

Another error can be produced by the non simultaneous sampling moments of the recorded signals. The maximum deviation could be 1 sample. In the case of the system described in (Chiculiţă and Frangu, 2015), this error source can be neglected, as the signals are simultaneously sampled.

Two more errors can also be neglected: the deviated value of the distance *L* will be compensated when the measuring software is calibrated, by comparison with a more precise device, and the deviation of the sampling period is insignificat, as it is produced by a quartz device.

An important effect comes from the last three terms of the relation (6). There is no analytical evaluation of this error, as function of the components added to the pavement excitation. Instead, an extensive set of simulations of the crosscorrelation, carried on with recorded vibration signals, produced the maximum delay error of 2 samples.

Considering all error sources, the maximum expected relative speed error is 2.5/80 = 3.1% for high speeds and 0.3% for low speeds. There is no experimental validation of this bound, so far. One can assume that the method is suitable mainly for low speed, but the decreasing pavement excitation, at low speed, makes this method work only above 20km/h.

4. EXPERIMENTAL RESULTS

The presented method was used for measuring the speed of a regular car, endowed with the vibration measuring subsystem described in (Chiculiţă and Frangu, 2015). Its purpose is to simultaneously diagnose the mechanical subsystems of the car and evaluate the status of the pavement, while running at traffic speed (up to 70km/h). The main advantage of using this method is to find the speed, for diagnosis reasons, without requiring data from other sensors of the car. 5 sensor nodes were installed on the car and the data were recorded on a laptop. The sampling period is 1ms and the useful band of the sensors is 400Hz.

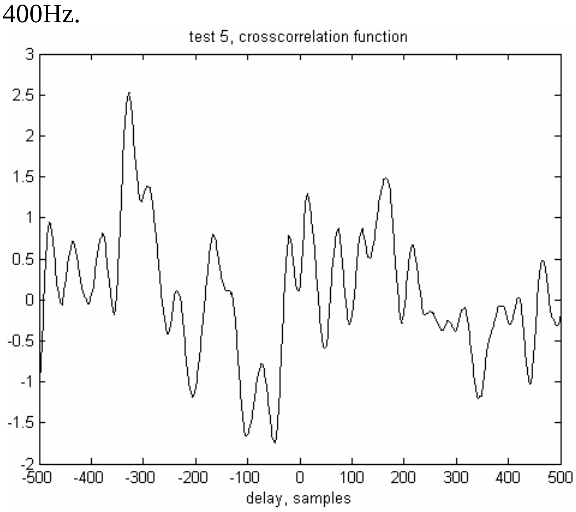

Fig.4. Crosscorrelation function between signals provided by the front and rear sensors, from (Chiculiţă and Frangu, 2015).

Figure 4, from (Chiculiţă and Frangu, 2015), presents an example of crosscorrelation function, between the signals provided by the front and rear sensors. The maximum corresponds to the speed of the car, experimentally validated. The argument of the maximum is 320 samples, which leads to a delay of 320ms and a measured speed of 8.1m/s (roughly 29km/h). On the same figure, one can observe a quasiperiodic phenomenon, produced by the engine shaft. Its period is 50ms, meaning its rotational speed is 20Hz (1200rot/min). For comparison, figure 5 presents a crosscorrelation function between signals recorded when running at a similar speed and shaft angular speed, but on a smooth pavement. The signal component produced by the engine overruns the component produced by the pavement. As a consequence, the delay corresponding to the maximum of the function is close to 0; it does not point to the speed of the car, but to the propagation delay of the engine vibrations.

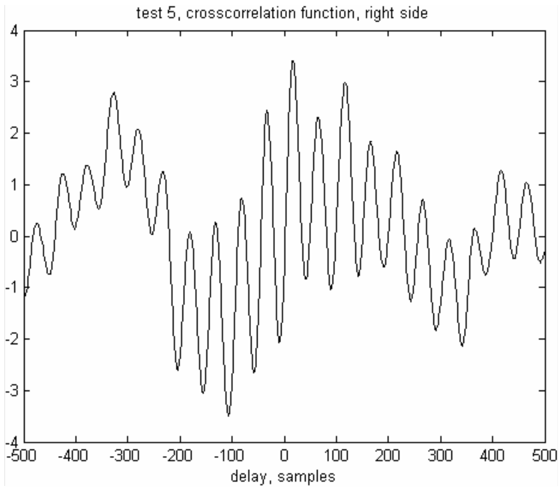

Fig.5. Crosscorrelation function between signals recorded when running on a smoother pavement.

5. CONCLUSIONS

The measuring method proves to be useful in some restrictive conditions: the vehicle is endowed with a vibration measuring subsystem, it runs at normal speed, and the pavement is not very smooth (it provides enough excitation). It is not suitable for values of the speed lower than 20km/h. Fortunately, this area is not interesting for the diagnosing device, intended to use the measured value of the speed. The expected relative error is 3.1% for high speeds and decreases for lower speeds. However, there is no experimental validation of this bound, yet. The response time of the measurement roughly ranges from 160ms for high speed to 1.6s for low speed.

The method was experimentally validated, excepting the error range. Future work will include a validation of the error range, a calibration and a new algorithm for reducing the response time for low speeds.

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