Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Performance analysis of an optical distance sensor for roll angle estimation in sport motorcycles

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Abstract: The roll angle is a crucial parameter for motorcycle dynamics. The ability of measuring it reliably in real time is an enabling technology for active control systems design for two-wheeled vehicles and for tire performance assessment. Nonetheless, it is quite difficult to devise the best trade-off between cost and precision and to choose the most appropriate sensor technology and lay-out. This paper analyzes if low-cost non contact optical distance sensors are a viable solution for measuring the roll angle. To use this method in sport applications some basic requirements must be satisfied, first of all the distance measurement must be reliable even at very high speed and under different lighting conditions. Our aim is to test a low cost optical triangulator with a single LED emitter and to show how the interference due to asphalt roughness in a condition of solar lighting and high speed affects the quality of its output.

1. INTRODUCTION AND MOTIVATION

Nowadays, four-wheeled vehicles are equipped with many different active control systems which enhance driver and passengers safety, some of which – such as the Anti-lock Braking System – have recently become a standard on all cars. In the field of two-wheeled vehicles, instead, such spread of electronic control systems is still in its infancy, as today only a few commercial motorbikes are equipped with ABS systems; moreover, the few ABS systems available are certified to work only when "panic brakes" occur on straight road. When moving to curves, the knowledge of the roll angle, that is the inclination of the vehicle with respect to the vertical direction, is needed. Therefore, to move a step further in active control systems for two-wheeled vehicle dynamics, the enabling technology comes from a system and method to estimate the roll angle in a reliable way and in real-time. Besides its usefulness in control system design, a reliable on-line measure of the roll angle might be employed in the racing context to assess the tire performance with respect to this fundamental variable. In fact (see e.g., (Cossalter, 2002), (Sharp et al., 2004)) the roll angle has a major impact in determining the lateral tire-road contact forces which ensure the stability of a motorcycle on a curve. In the open scientific literature very little has been published on this topic so far. In (Gasbarro et al., 2004), an approach for estimating the whole vehicle trajectory is proposed which employs a vision system made by cameras complemented with MEMS accelerometers. The other approach currently used by racing teams is that of employing a Global Positioning System - GPS - (or a differential GPS) to estimate the complete trajectory and derive from this information the roll angle as a by-product. Both these approaches need expensive sensors systems and, most important, are not capable of providing the roll angle measure in real time. Some other approaches may be found in the patent literature. For example, in (Hauser et al., 1995), (Schiffmann, 2003), (Gustaffson et al., 2002) and (Schubert, 2005) some approaches are described, whose common purpose is to devise robust estimation methods with low cost (and small size) equipment. In (Miekley et. al, 2006) this problem is solved using gyroscopes and a simplified model of the motorcycle dynamic to correct the bias drift of the signals. While all of these algorithms can be implemented to obtain an indirect estimation of the roll angle, by means of distance measurements the *real* value of this dynamic parameter can be obtained. As it is clear from the above discussion, roll angle measurement capability is very important in commercial applications to calibrate low-cost versions of roll-angle estimation algorithms while, in the racing context, it can provide a reliable measure to be employed for tire characterization and performance assessment. The aim of this work is to analyze the performance limits of the considered optical sensor in order to assess its suitability for this kind of application. As a matter of fact, motorcycles are a very demanding application for measurements systems, because of significant vibrations due to the engine, high vehicle speeds and different asphalt conditions in which they happen to operate.

2. PROBLEM SETTING

In a motorcycle, the attitude is described referring to a moving frame centred in the vehicle center of mass G (see Fig. 1). The attitude of the vehicle is represented by the roll-pitch-yaw angles: the roll angle φ measures the rotation around the x axis, the pitch angle θ that around the y axis and the yaw angle ψ that around the z axis (Cossalter, 2002). To measure both pitch and roll angles, one may employ the difference in the distance from the asphalt to two points, which are aligned (*i.e.*, they measure the same distance from the ground) when both roll and pitch angles are equal to zero.

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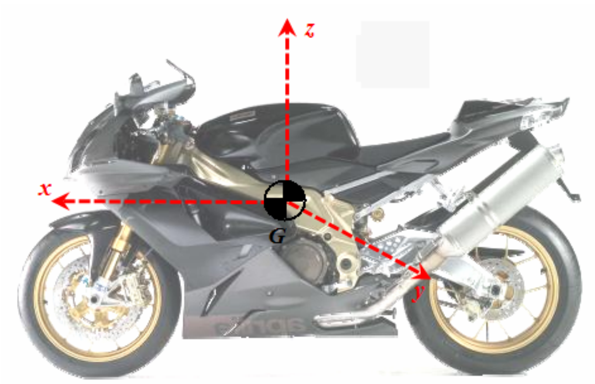

Fig. 1. Motorcycle frame: representation of the body-reference moving frame associated to the motorcycle.

Two distance sensors placed in the perpendicular plane with respect to the motorcycle symmetry plane suffice to compute the roll angle. At zero roll angle, the two distance sensors should be mounted at a common distance H_0 from the asphalt and with a displacement L one from the other (see Fig. 2). The distance measured from these sensors can be expressed as a function of the roll angle φ as

$$\begin{aligned} d_1 &= H_0 + L/2 \cdot \tan(\varphi) \\ d_2 &= H_0 - L/2 \cdot \tan(\varphi) \end{aligned}. \tag{1}$$

Combining the two measured distances d_1 and d_2 and considering the triangle ABC in Fig. 2, the roll angle can be expressed as

$$\varphi = \arctan\left(\frac{d_1 - d_2}{L}\right). \tag{2}$$

Note that in deriving (2) we are neglecting the influence of the pitch angle on the roll motion. This hypothesis is not limitative in our case, as the tests are performed on straight road and at relatively low forward speed (below 100 km/h). However, in the case of a racing vehicle the value of the pitch angle should be explicitly taken into account. The mounting parameters H_0 and L should be determined so to minimize the uncertainty in the measurement of the roll angle within the range of interest. The optimal values are a function of the characteristic of the adopted sensors. In our work, H_0 and L are chosen to minimize the measurement uncertainty around zero roll angle according to the constrains due to both the measuring range of the sensors and the available space for physical mounting.

3. EXPERIMENTAL SETUP

To obtain a non contact measure of the distance from the ground, the electro optical technology seems to be the ideal choice. As a matter of fact, the output of an optical distance sensor can be extremely accurate and rapid enough for this use. In the considered application, the sensor size is a significant issue, as the motorcycle does not offer many mounting points and has limited free space. Therefore, our aim, is to test a low cost, off-the-shelf, and very small optical sensor with appropriate resolution in order to investigate if it allows to obtain a roll angle measurement which is reliable in all the desired conditions (*i.e.*, for high vehicle speed and different lighting conditions).

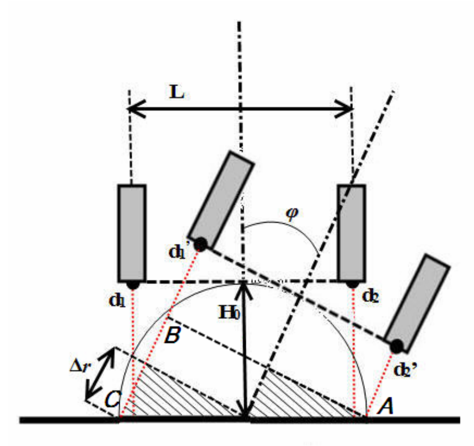

Fig. 2. Roll angle measurement using two distance sensors placed in the perpendicular plane with respect to the motorcycle symmetry plane.

3.1 Optical sensor characteristics

First of all we briefly recall the working principle of an optical distance sensor (Donati, 2004; Doeblin, 2004) based on the triangulation method. A schematic view of the optical triangulator is shown in Fig. 3: the distance from the target is converted into a transverse displacement of the beam focused on the photodetector, which – typically – is a Position Sensitive Device (PSD) sensor. The light emitter can be either a LED or a high-coherence optical source such as a laser.

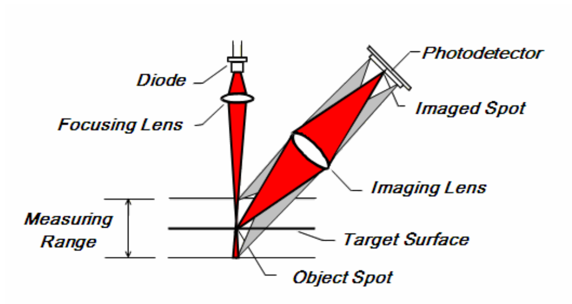

Fig. 3. Schematic diagram of an optical distance sensor.

The sensor tested in this work has a LED emitter with a wavelength in the near infrared field ($\lambda \approx 780$ nm). We point out that the considered sensor is a compact, low-cost, off-the-shelf device, whose original field of application is robotics: thus, on one hand the size constraint is as relevant as in motorcycle applications, but, on the other hand, robotics has no need of guaranteeing that the output is reliable also at high target speeds. The main parameters of the tested sensor are reported in Table 1.

Table 1. Parameters of the low cost optical sensor.

Parameter	Value
Distance range	15 cm – 100 cm
Output voltage	0.5 V – 2.5 V
Quantization	0.02 V
Modulation frequency	1 kHz

The emitter output is amplitude-modulated at a frequency of 1 kHz. Modulation is fundamental to minimize the detrimental effects of solar light on the sensor output. It is well known that the light intensity of the sun has a power spectrum limited around DC frequency. Thanks to the modulation procedure, the signal that contains the information of interest is shifted to the high frequencies, thereby increasing the *signal to noise* (S/N) ratio in the optical detection process. To mount the sensor on the motorcycle, an aluminium case was deployed, which is needed also to house the battery supplying the sensor. In fact, a power supply independent from the battery of the motorcycle is necessary to avoid electrical interference caused by voltage coupling and disturbances (see Fig. 4).

The aluminium case is also helpful to shield the measured signal against electrical noises. Clearly, one has also to employ shielded cables to avoid that the measurement is corrupted from radiated electromagnetic coupling which may occur. As noted in Section 1, motorcycles are very noisy measurement environments, in which accelerations and electrical coupling significantly affect the signal reducing the S/N ratio. This means that great care must be taken in the design of both the sensor and its cabling.

Fig. 4. Aluminium case containing the sensor and the battery supply.

3.2 *Test Vehicle and Data Logger*

All the tests were carried out on a hypersport-class motorcycle, namely an Aprilia RSV1000 (see also Fig. 1). The motorcycle has an on board Electronic Control Unit (ECU) with both analog and digital inputs sampled up to 1 kHz. The analog inputs can be acquired at 10 bits or 12 bits resolution in a range 0-5 V. In our application, we chose to connect the sensors to the 10 bits input channels as the internal quantization level of the sensor (see Table 1) does not allow to exploit the 12-bits precision of the acquisition board.

3.3 *System setup*

The main difficulties in the system set-up are caused by the lack of mounting positions for the sensor. The best trade off between the constrains due to the optimization of the resolution and the available mounting points is the hooking of the rear stand, as shown in Fig. 5.

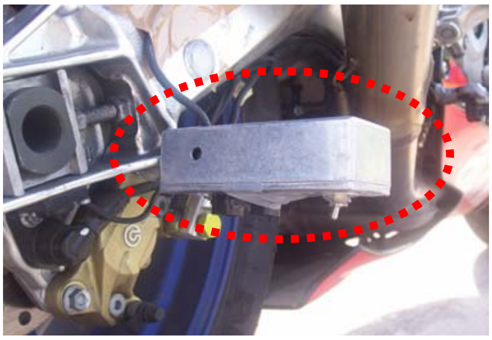

Fig. 5. Sensors connection: the optical distance sensors are mounted (see oval box) at the hooking of the rear stand.

Note that, to obtain a symmetrical measurement system both for positive and negative roll angle values each sensor must be connected with its receiver and emitter placed at the same distance from the symmetry plane of the vehicle. This led to the choice of the mounting parameters H_0=28cm and L=36cm. Finally, to be able of estimating the asphalt roughness, the system is completed with a high-precision (and high-cost) optical laser distance sensor whose characteristic parameters are reported in Table 2.

Table 2. Parameters of the high precision distance optical sensor.

Parameter	Value
Distance range	5 cm – 35 cm
Beam type	Point
Resolution	0.01 mm – 0.4 mm

4. EXPERIMENTAL RESULTS

In this section we analyze the signals measured during a test carried out on a straight line track. The sensor was tested in different conditions of both lighting and vehicle speed.

First of all the sensors have been calibrated employing as reference distance the output of the optical laser distance sensor. By means of quasi-static tests, it was possible to experimentally compute the characteristic curve of the low-cost optical sensor, *i.e.,* the mapping between output voltage and measured distance. This curve has been computed by measuring the reference distance through the high precision optical sensor. To minimize the non linear distortion effects, all the tests were carried out at zero roll angle. In Fig. 6, the characteristic curve of the low-cost optical sensor is shown: the dotted curve is the interpolating second-order polynomial which has been used to fit measured data.

Once the mapping between voltage and distance has been estimated, several tests have been performed to ascertain if the vehicle speed may affect the output signal of the distance sensor and if there are other significant sources of noise coming from the external environment.

To better isolate the problem, the tests were all taken in the same predefined straight-line freeway section, which was covered at different constant speeds, in both directions. Thank to this procedure, in a round trip each of the sensor is tested once with solar lighting and once in the vehicle shade. Note that all these tests should, in principle, provide exactly the same values of measured distance.

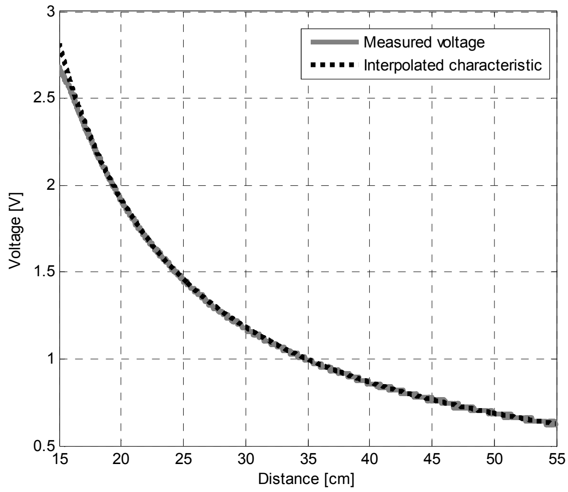

Fig. 6. Characteristic curve of the optical distance sensor tested in the application.

Fig. 7 shows the measured distance signals of the right sensor at two different speeds of 10 km/h and 70 km/h, respectively. The results in the top plot show that the condition of solar lighting and low speed does not affect the S/N ratio of the measured distance, thus maintaining a very good accuracy level. This also happens with the combination of shadow and high speed. The main problem appears at a motorcycle speed of 70 km/h with solar lighting: in fact (see the bottom plot in Fig. 7), in this condition the measured distance is clearly affected by a significant noise which makes the sensor output highly unreliable. After the performed analysis, we can conclude that a significant optical interference phenomenon exists, which appears to be due to a combination of high vehicle speed and strong solar lighting. To further investigate the main source of the problem, consider the results shown in Fig. 8, where the optical sensor output in solar lighting conditions and motorcycle speed v=70 km/h for different asphalt roughness levels is displayed.

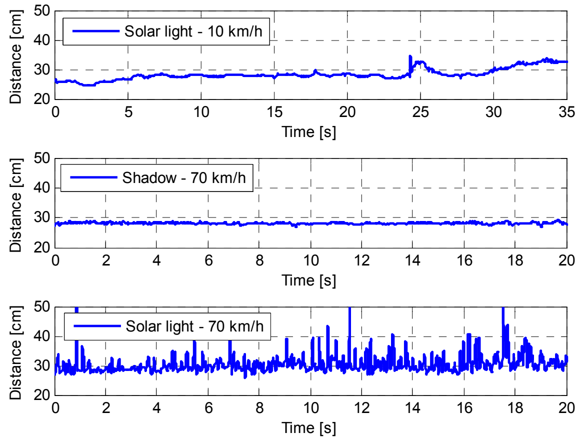

Fig. 7. Optical sensor output in three different conditions of lighting and motorcycle speed: solar light and low speed (top); shadow and high speed (middle); solar light and high speed (bottom).

As can be seen, on low-roughness asphalt the sensor provides a consistent output also for this speed value. Hence, the sensor performance limits seem to be due to a combination of vehicle speed value and asphalt roughness.

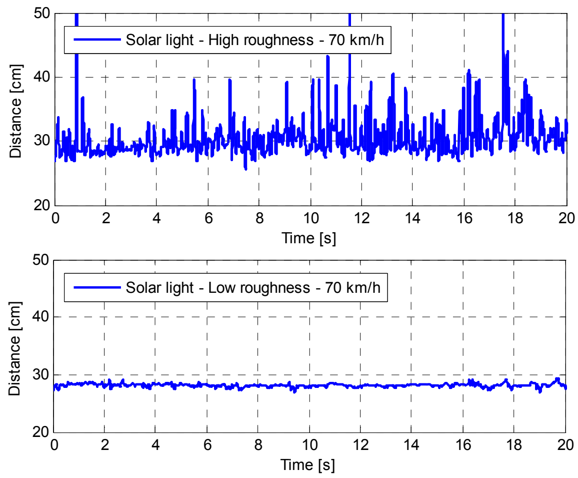

Fig. 8. Optical sensor output for different asphalt roughness levels, in solar light conditions and motorcycle speed v=70 km/h: high roughness (top) and low roughness (bottom).

The performance degradation can be due to the fact that the interaction between the solar light diffused from the asphalt (which changes according to the roughness level) and the motorcycle speed induces a modulation of the environment lighting that may have some frequency components also around the modulation frequency of 1 kHz used by the sensor. If this is the case, then the resulting interference justifies the significant decrease in the S/N ratio of the measured distance signal which we experimentally encountered. To provide a rigorous explanation of this phenomenon, a measure of the asphalt roughness must be obtained. To do this, we employed the distance measure provided by the high precision optical sensor. As we are interested in recording a distance signal with low frequency components, the roughness is measured at very low and fixed motorcycle speed (3 km/h). Note that the low speed also allows to fully exploit the resolution of the high precision optical sensor as it reduces the effect of the low-pass filter embedded in the sensor electronics and avoids aliasing phenomena.

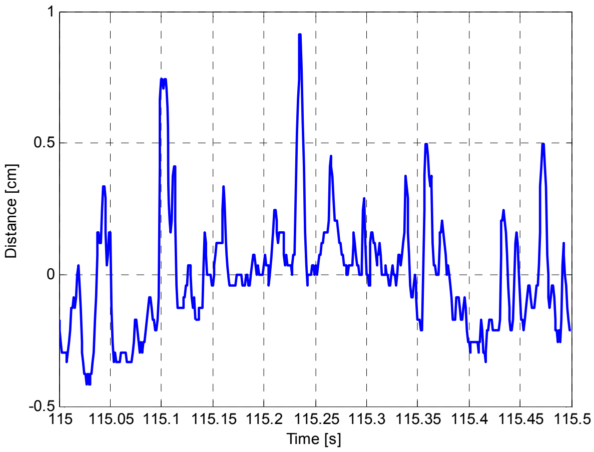

Fig. 9. Asphalt profilometry by means of the high precision optical laser sensor in a test carried out at constant vehicle speed v=3 km/h.

The results of this test are shown in Fig. 9, on a 0.5 s time window, which allows to appreciate the high resolution of the optical sensor output. As the modulation frequency of the emitter of the tested optical sensor is known, in the next section we investigate if our hypothesis of frequency coupling between sensor distance measurements and solar lighting is in fact a function of the vehicle speed.

5. PERFORMANCE LIMITS ANALYSIS

The optical noise due to solar light interference can be modelled as a signal with the same frequency content of the asphalt roughness translated according to the vehicle speed. In Fig. 10, the power spectrum of the asphalt roughness computed from the distance measurements of the high precision optical sensor for a constant value speed of 3 km/h is shown. At very low speed, the signal spectrum has significant frequency components only up to 100 Hz. Thus, for low speed values, the light modulation due to the asphalt roughness does not produce an optical noise that overlaps the LED beam on the photo detector even in a condition of high intensity lighting. This confirms the results shown in the top plot of Fig. 7.

5.1 Reconstruction of the roughness as a function of space

To confirm that the asphalt roughness shown in Fig. 9 has the foreseen evolution as a function of the motorcycle speed, we need to show that, as the vehicle speed increases, significant components appear in the signal spectrum at higher frequencies.

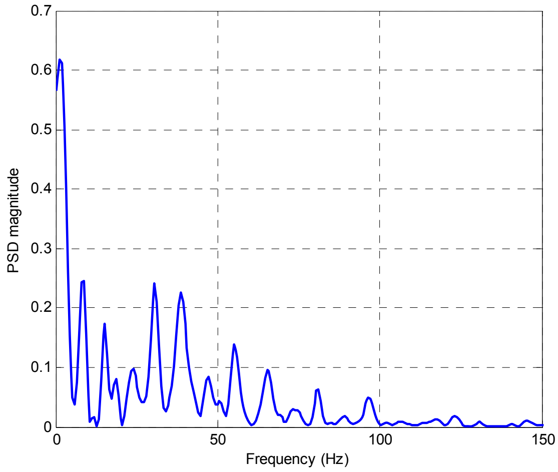

Fig. 10. Frequency content of the asphalt roughness at 3 km/h.

To do this, it is useful to express the asphalt roughness as a function of space instead of time. To this end, note that the covered distance in the tests can be computed as

$$S = t \cdot \overline{V} \ , \tag{3}$$

where the S represents the new space signal, t is the original time signal and $\overline{V}$ is the average motorcycle speed in the considered test section. Roughness as a function of space obtained from the distance measured at 3 km/h is shown in Fig. 11.

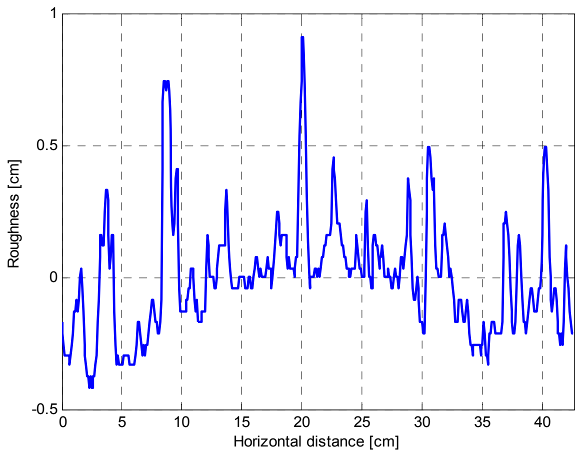

Fig. 11. Asphalt roughness as a function of distance.

5.2 Influence of the motorcycle speed

Based on the previous section results, we can study the roughness signal for different motorcycle speeds and analyze the power spectrum of the resulting profile to determine a *critical* value of the vehicle speed. This is the velocity value that causes interference from the asphalt roughness to fall at such Fourier frequency (~1 kHz) where the coherent optical detector is sensitive to this disturbance. To do this, we can employ the data measured at 3 km/h to extract information about the roughness spectral density at different speeds. By means of (3), if – for fixed covered space S – we change the value $\bar{V}$, we can compute a new time vector t. Thus, we obtain the asphalt roughness as a function of speed in time domain, based on which we compute the corresponding power spectral density. Fig. 12 shows the asphalt roughness frequency content at different vehicle speeds. As can be seen in the middle graph of Fig. 12, the estimated critical speed in this case is v=15 km/h. Note, in fact, that for v=15 km/h the asphalt roughness has a significant frequency component at the emitter modulation frequency of 1 kHz and that the upper bound on the frequency content shifts forward as speed increases as expected. This confirms our hypothesis and explains the experimental results discussed in the previous section (see Fig. 7). Finally, by analyzing Fig. 13, which shows a test carried out at increasing speed (from 0 to 25 km/h), one may assess that 15 km/h is indeed the critical speed value above which the distance sensor output starts being highly affected by the solar lighting diffused from the asphalt. This analysis allows to conclude that the light diffused by the asphalt creates a speckle pattern that can be studied as a signal having the same profile as that of the asphalt roughness. This pattern produces an optical noise signal whose spectral content varies as a function of the vehicle speed and which possesses very high frequency components that overlap the emitted beam at the optical distance sensor modulation frequency.

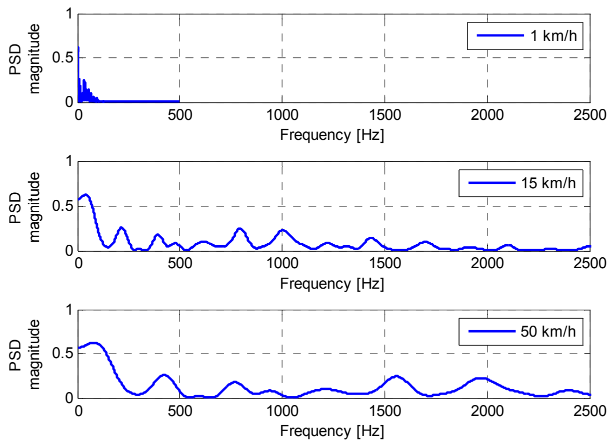

Fig. 12. Asphalt roughness frequency content at different speeds.

6. CONCLUDING REMARKS AND FUTURE WORK

In this paper, a compact, low cost off-the-shelf distance optical sensor to measure the lean angle of a motorcycle has been tested. The performance limit due to the interaction between the light diffused by the asphalt and the motorcycle speed was experimentally analyzed: solar lighting may produce an optical noise significantly reducing the S/N ratio of the measured signal. From the application viewpoint, the performed analysis revealed that the tested sensor provides good performance and a reliable output also at high speeds and with significant solar lighting if used on a low roughness asphalt.

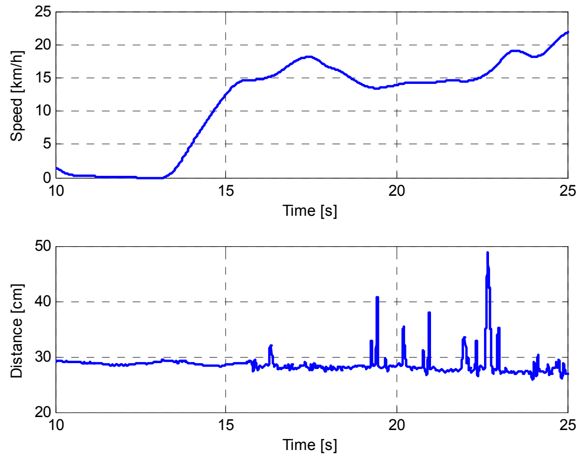

Fig. 13. Motorcycle speed (top) and distance measured by the low cost optical sensor (bottom).

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