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RELIABILITY MEASUREMENT ASSESSMENT OF BRAKING PROCESS ROAD TESTS

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Summary

The paper presents the issue related to road test of vehicles' braking process. The most often used optical correlation sensors by the Corrsys-Datron company were discussed. While assessing the accuracy of road tests, the problem of periodical checking a measurement track arises. Because of formal reasons, calibration procedures certified by a manufacturer are required. The paper describes a test bench method for checking optical correlation sensors using the elements of a measurement bench for testing the brakes. Movement of the vehicle was simulated using the rotational movement of an inertia disc controlled with an inverter drive system. The test in the described bench can be used to verify the accuracy of the sensors in the periods between calibrations as well as to carry out tests expanding the knowledge on characteristics of the used sensors while providing the essential operational information. The bench may be an alternative to the organisationally troublesome control measurements performed under road conditions. The sample results of tests of three optical correlation sensors on the stand were presented and related to the results obtained in the course of the road tests. The use of modern micromechanical accelerometers in these tests was also discussed. It was indicated that the result of the measurements is influenced not only by the accuracy class of the sensor but also a manner of the sensors' fitting, present interferences and manners of their filtering.

Keywords: road measurements of vehicles, braking dynamics, optical speed sensors, accelerometers

1. Introduction

Road tests of the braking process dynamics of vehicles are mainly related with measurements of three values: instantaneous speed of the vehicle, its deceleration

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and travelled distance. These figures, linked mathematically with each other, can be measured and recorded using a single sensor of vehicle speed. In the measurements of speed and distance, optical correlation heads, known since the mid 80's, are most often used. Launched on the automotive research market by the Corrsys-Datron company and currently continued by the Kistler company [7], they remain a constant component of professional kits for testing of vehicles' dynamics. They replaced the old solutions like "the fifth wheel" and now they withstand competition with microwave and radar sensors as well as methods based on the GPS satellite positioning system [3]. The patented principle of the optical correlation heads' operation is still being improved, and the sensors using it expanded their scope of application. They have become resistant to adverse road conditions, increased operation reliability on a variety of surfaces and reduced the size. There appeared versions adapted to all scopes of tests of land vehicles – wheel and railway ones.

The paper describes a test bench method of assessing the optical correlation sensors' parameters, which is an alternative to calibration procedures offered by the manufacturer. Effects of bench measurements conducted in the Department of the Department of Vehicles and Fundamentals of Machine Design of the Łódź University of Technology in cooperation with the Braking Systems Laboratory of the Automotive Industry Institute in Łódź were used.

The obtained results of bench tests were used to verify the example road testings.

2. Use of optical correlation sensors in road tests of braking process

The optical correlation sensors have been known on the vehicle tests market since the 1980's. Initially, the process of displacement of the previous solutions like "the fifth wheel" occurred relatively slowly because of high prices of the new measurement technology.

The optical correlation technology allows for non-contact, sliding-free measurements of speed components by observing ordinary surface, on which the vehicle travels. The surface does not require the application of a raster or markers. The sources of information are stochastic changes of contrast occurring on any surface. Along with the improvement of sensors, changes in their optical systems and the range of the used spectrum, limits of a carriageway also decreased.

Current versions of the sensors are able to measure also on seemingly homogeneous optical materials such as water and smooth surface of rails.

The principle of operation is based on lighting the surface with a strong stream of coherent light and observation of the reflected rays going into the optical receiving system. The illuminated image surface passes through a lens and an additional aperture. The optical system is designed so that it does not require precise focusing, while working usually at a distance of 30 to 40 cm from the surface with a maximum tolerance of several centimetres. The rays reflected from the surface go then to a prismatic screen, which separates the image and directs them to photocells. Modulation of photocell light is connected with the movement of the illuminated carriageway structure and the optical system constants (a screen constant and the magnification of a projection system). The frequency of the electrical signal in the photocells carries the information about the motion relative to the surface. In order to extract the useful signal, slow-varying components, which are treated as an interference (they may arise from e.g. fluctuations in external lighting or changes in surface reflectance), are filtered. The fluctuations are eliminated using two photodetectors behind the prismatic screen, operating in a differential system. The final signal has only a component resulting from the observation of a moving image of the carriageway microstructure. Output signals from the sensor are: velocity relative to the surface shown as an analogue voltage signal and a digital signal in the form of a square wave carrying information about the travelled distance. The calibration of the sensor involves determining the degree of changes in the output voltage depending on the speed, linearity of this processing, and – in relation to the distance measurement – determining the number of pulses generated by the sensor on the 1 m long road. The manner of use of these two signals depends on the user. For example, by recording the voltage speed signal constantly, the braking deceleration may be obtained after differentiation. The braking distance may be read after integration of this distance. Summarising the road pulses in a digital counter system is also possible. By differentiating the digital signal of the road, the vehicle speed can be calculated. Using differentiation procedures, an effective filtration of appearing noise should be taken care of.

The sensor design does not contain moving elements and does not have a mechanical contact with the surface. This allows it to maintain efficiency in the long term, even at the intensive operation.

Three measuring heads (fig. 1) from different periods of production but keeping the same design features were chosen for the tests described herein.

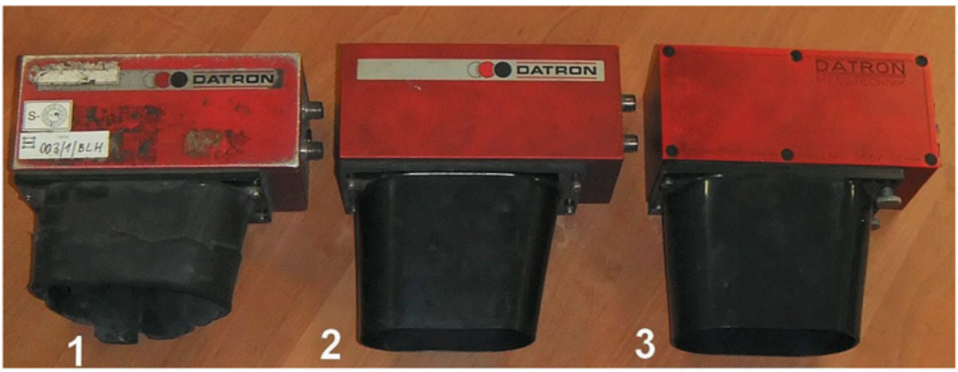

Fig. 1. View of the measuring heads used for tests 1 – Correvit Datron LS1, 2 – Correvit Datron DLS1, 3 – Correvit Datron LM

3. Bench tests

Each measurement system requires periodic calibration and check. In the case of optical correlation sensors, their verification can be performed in two ways: by travelling the standard road section or by the test bench method, using a rotating drum [2]. In the first method, you must have access to the standard road section. Checking the sensors in the speed measurement mode remains a problem because it is difficult to provide standard drive speeds, at which readings can be made. The firmware provides a calibration procedure available for the user involving driving the measured road section (from 100 m to 10 km) at a low speed and recording the number of pulses generated by the sensor. The beginning and the end of the measurement should be signalled using light barriers placed at the section ends.

In the test bench method, a stable linear speed patter, which is a rotary drum track, is used additionally for calibration. Under repeatable laboratory conditions, drive speeds from a few km/h to the maximum one for a given sensor – e.g. 400 km/h – can be reconstructed.

In order to assess the reliability of the possessed sensors, a bench tests idea was implemented. In order to simulate the diver at various speeds and travel the road sections, an inertial bench for testing car breaks in the Braking Systems Laboratory of the Automotive Industry Institute in Łódź (PIMOT-Łódź) was used. The main used element of the bench are rotary inertial masses in the form of discs, driven electrically via an inverter with velocity feedback. The track observed by the sensor is side surfaces of a few connected discs, painted with flat colour with the exact measurement of the disc diameter, its circumference (D = 3109.93 ± 0.36 mm) was calculated, which was the standard, measurement, unit road section. Multiple travelled standard sections were inspected with an additional optical sensor (a reflective photocell) and a counter circuit in a data acquisition modul. In accordance with the suggestions of the sensor's manufacturer, it was decided to perform test "drive" on the bench on the section close to 1000 m, which corresponds to 323 rotations of the inertial disc.

In order to create a standard linear speed from the rotating discs of known circumference, an appropriately high motion stability had to be ensured. The inverter drive system with velocity feedback used on the bench enabled this. A significant discs' moment of inertia also had a stabilising effect. The rotational speed of discs was measured using the encoder with 60 decimals.

The first stage of the test of the sensor involved "travelling" the standard section and recording the number of pulses generated by the sensor. A 32-bit counter of the data acquisition modul, which (depending on the type of measurement) could also count pulses from a 60-field encoder disc to assess precisely the standard speed, at which the bench reproduces, was used.

The second test involved reading the speed recorded by it. To do this, the bench reproduced a stable, standard drive speed, and output voltage from the sensor was recorded via a laboratory digital voltmeter with a function of transmission to a file. The accuracy class of the gauge in the used range of 4V is ±(0.06%+2d), which exceeds the parameters of the popular 12- and 16-bit data acquisition moduls, while providing better thermal stability of measurement and interference resistance.

Both stages of the test programme were repeated many times, in order to achieve a satisfactory material for statistical processing [1]. For example, in order to confirm the stability of the speed, 12 measuring cycles, 10 s each, were recorded. The number of pulses recorded each time from the encoder served to calculate the track speed in m/s and km/h. At the same time, series of numbers specifying output voltage from the sensor were also recorded.

Figure 2 shows all the elements used for bench tests of the optical correlation sensors shows schematically in Figure 2, while Figure 3 shows the view of the most important fragment of the bench.

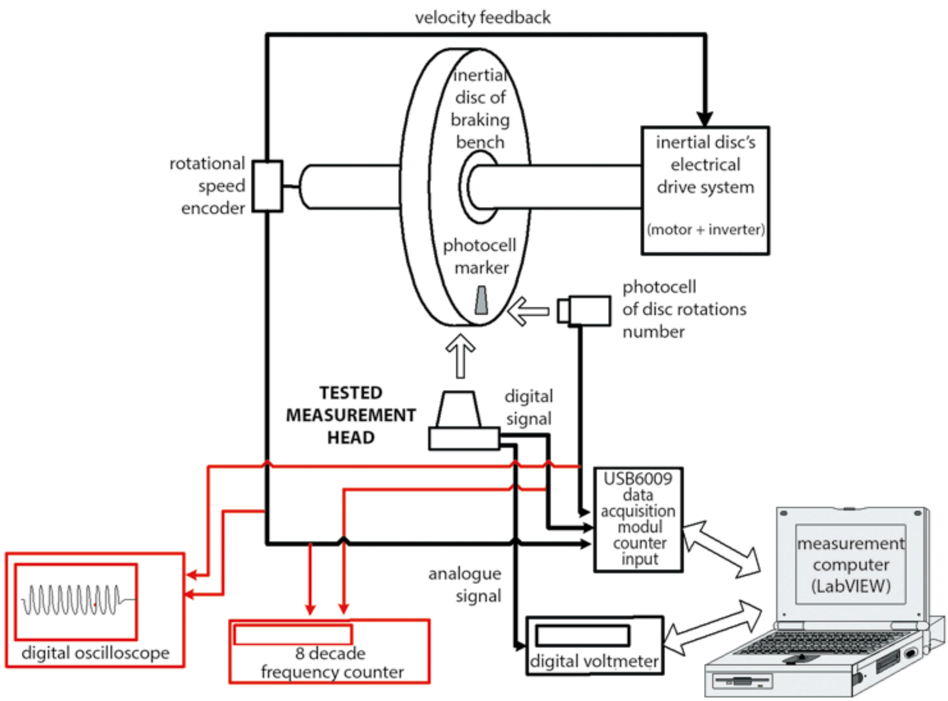

Fig. 2. Diagram of a bench for optical correlation heads tests

Checking the heads as the road sensors involves counting the pulses generated by them on a digital output. Testings involving virtual travelling a test standard section with length of c. 1 km were repeated five times for each of the speeds: 20, 60 and 100 km/h. Because the distance measurement should not be dependent on the motion speed, the judgement had to be confirmed. The number of registered pulses at travelling 323 disc circuits was

c. 400 thousand – therefore, the used counter circuit had to have an appropriate capacity. Information on the travelled distance resulting from the disc circumference with the amount of the pulses generated by the head allowed to calculate the scale coefficient for the road expressed in impulses per metre. The manufacturer specifies the value to c. 400 imp/m.

The tests on the bench, above all, confirmed the high reproducibility of the checked heads. While travelling test section for each of the three speeds five times, the registered speed meter states showed a deviation from the average value no greater than 0.5%.

For example, for the sensor used in the road tests discussed later in the paper (sample shown in Fig. 8), the results of counting the road pulses (403,000 imp.) on a simulated test section with a length of 1004.51 m for 3 adopted speeds (20, 60 and 100 km/h) helped to determine the average conversion ratio as 401.2 imp/m. The volume declared by the manufacturer was 400 imp/m – so the difference is 0.3%.

In conclusion, that would be the difference in the road measurement results if the recalibration was not done and only the data supplied by the manufacturer were kept. In real conditions of road tests, this difference can be considered negligibly small. Such difficult in control factors as: weather conditions' influence, heterogeneities of surface, tyres and brakes' temperature affect much more significantly the final measurement result.

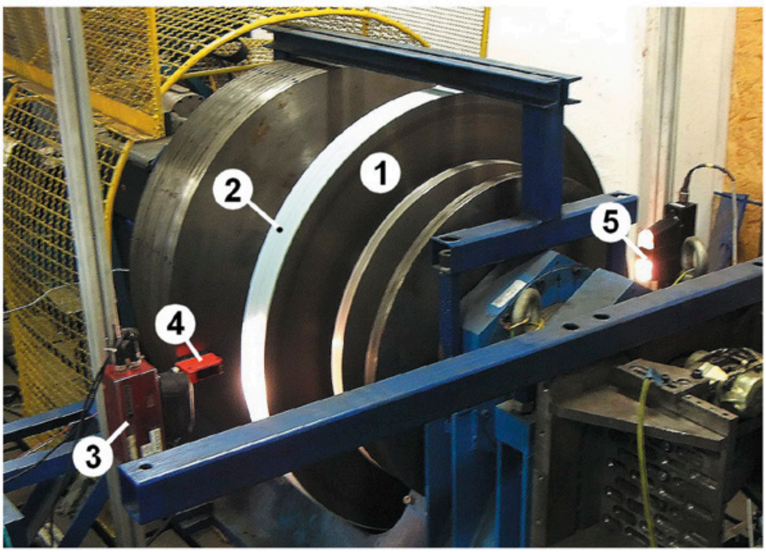

Fig. 3. View of the inertial bench for brake testing, adapted to testing correlation optical heads:
1 – rotary disc, which is an analogue of the travelled road,
2 – surface forming a shield covered with paint, cooperating with the tested head,
3 – the tested head Correvit Datron LS1,
4 – reflective photocell counting full rotations of the disc,
5 – the second head (S-400 type) for control purposes

The bench tests also allow to assess the effect of noise generated during the operation of the sensor at its speed output. The fact that all analogue signals recorded in such a difficult measurement environment, which is the car, are affected by noise is obvious. Interferences appear in different places of the measurement track and require filtration in real time or at the final data processing. Their sources are the very sensors, interferences in the vehicle cabin circuits, the impact of electromagnetic fields (e.g. from ignition), poorly shielded computer equipment, etc. On the prepared bench, using a digital oscilloscope, the changes of the output signal generated by the very, isolated from the circuit the sensor can be estimated.

Example of such a course, for the speed range of 10-150 km/h are shown in Figure 4.

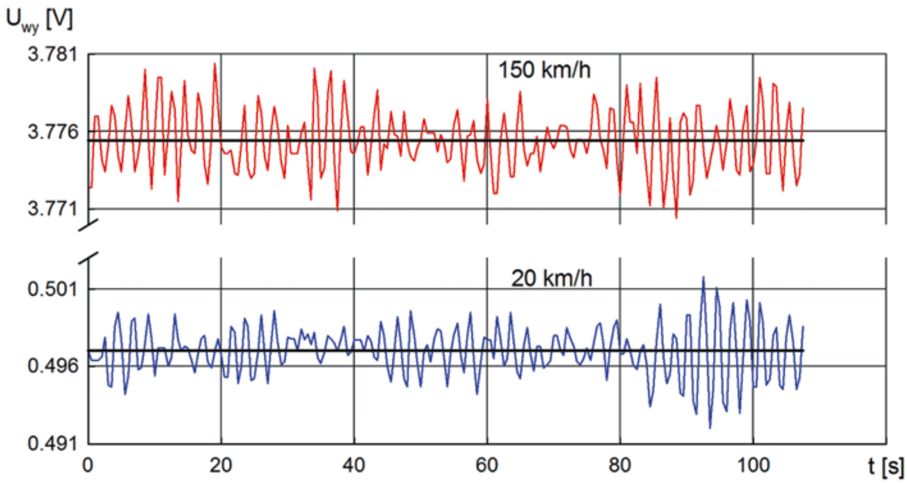

Fig. 4. Examples of variability of voltage speed signal U_{wy} observed in the conditions set out on the bench. The upper course (red colour) V = 150 km/h, the lower course (blue) V = 20 km/h, black lines – average value

Speed courses show changes of amplitude independent from the output signal level. This means that their influence on the final result of the measurement will be greater when the recorded speeds are smaller. For the speed of 20 km/h presented in Figure 4, the value of the fluctuations does not exceed 1%. These changes are periodic, without slow-varying components – they are relatively easy to filter and with a longer time of record, they do not affect the calculated average.

Using sufficiently long records, it was assessed how the measurement head converts the speed into voltage. Measurements were made for 15 different speeds ranging from (10 ÷ 150) km/h. The result of counting the pulses from the encoder installed on the inertial disc shaft during a 10-second test was considered the actual value of the set speed. The recorder rotation angle was converted on the road thanks to the precise knowledge of the disc circumference. During the same test, the output, analogue signal (200 samples) was recorded, which after averaging, was treated as a reading of the tested head. The difference of these two values is an absolute error, which is shown in Figure 5.

The same measurements were used to determine the processing function of the sensor, check its linearity and calculate the relative deviation. The percentage relative deviation was calculated from the absolute error referred to the actual speed value.

This was shown in Figure 6. The high sensor precision – entirely within the value of 0.2% declared by the manufacturer – draws attention.

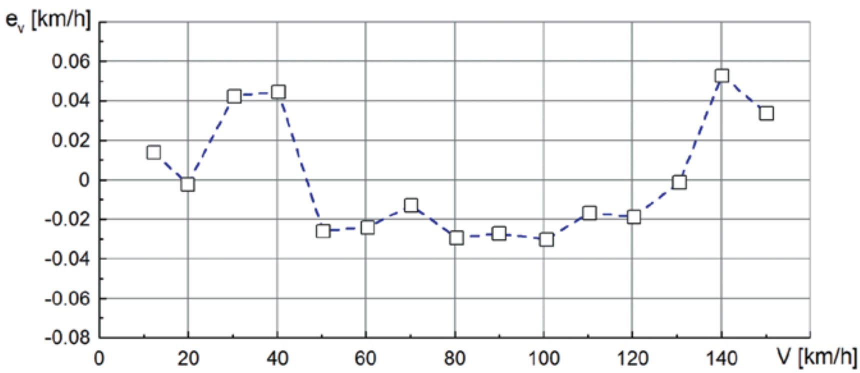

Fig. 5. Absolute error of the speed e_v measurement for different set speeds – the result of the bench measurements

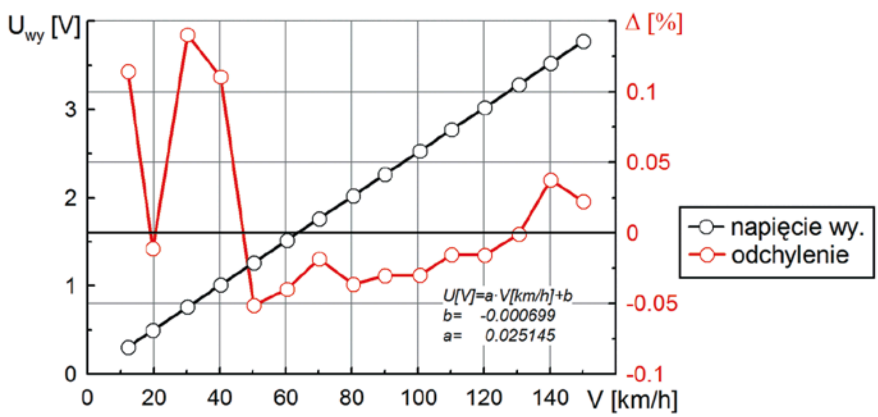

Fig. 6. Results of measurements of the voltage signal of the speed U_{wy} and the calculated percentage relative deviation Δ

Legend: napięcie wy. – output voltage

odchylenie – deviation

4. Effects of use of the correlation optical sensor in the road tests

As an example of the road tests, breaking of the coach equipped with an ABS/ESP device on the surface of the step variable adhesion coefficient from the value of $\mu = 0.6$ to $\mu = 0.3$. This test is performed to verify the adaptability of the ABS/ESP algorithm to the changing surface conditions [5]. In addition to the obvious temporary record of the vehicle speed value, the course of longitudinal deceleration and braking distance are also interesting – that is a typical set of results for testing the braking process. The record, due to the research goal, which was testing the prototype [6], was executed with an increased sampling rate of 1 kHz. In standard road tests, phenomena dynamics allows slower sampling – with a frequency of 100 Hz. As the speed sensor, the correlation optical head Datron DLS1 installed in an unusual place – under the chassis, near the centre of the vehicle mass – was used. Such a location, in spite of the many advantages (sensor protection from the weather conditions, minimising the impact of pitching of the body, easy interpretation of results when driving on curved tracks), is possible only in specially adapted test vehicles (Fig. 7).

Fig. 7. The measurement head Datron DSL1 mounted in the hole inside the coach's carrier

The consequences of clarifying the metrological parameters of the measurement head can be shown on the example of calculating the braking distance of a road test shown in Figure 8. The numerical integration using the trapezoidal rule was conducted from a fixed point in time, when the force on the brake pedal firmly reached 0.3 dN. The end point was at the end of the record, when the vehicle was in place and the road was not increasing. Three speed courses were used:

1) unfiltered, converted according to the factory calibration factor,
2) filtered using the moving average method with a parameter of 200 ms (ensemble average width)
3) unfiltered, but converted according to the new calibration factor of speed, received on the bench (Fig. 6).

The obtained results are shown in Table 1.

Table 1. Comparison of the results of braking distance calculation

Speed course no.	1	2	3
Braking distance [m]	59.187	59.194	58.791

The results of the integration were deliberately left with unrealistically large number of digits, to show how small is the difference between the calculated braking distances. The results 1 and 2 prove the random and symmetric nature of the interferences and the effective method of their eliminating using the moving average method. The fluctuations of the output signal, both positive and negative ones, disappear after filtering, which improves the graph visually. This is shown enlarged in Figure 8. However, they do not affect the integral value.

The difference between the values 1 and 2 and the value 3 results from a new calibration factor and is less than 0.7%.

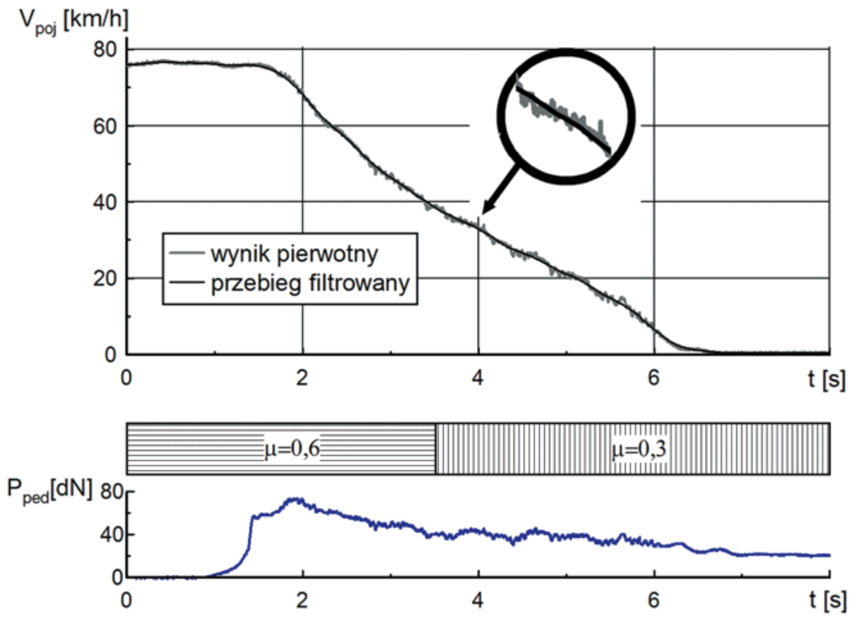

Fig. 8. The record of the braking process of the coach on the surface of the step change in adhesion coefficient μ = 0.6→0.3 (upper chart – the vehicle speed V_{poj}, lower chart – force on the brake pedal P_{ped})
Legend: wynik pierwotny – original result
przebieg filtrowany – filtered course

In addition to speed and distance, the third parameter describing the braking test is deceleration. The simplified procedures of road tests calculate the deceleration as average based on selected points of the braking process – the initial and final speed 40 and 20 km/h or 80% and 10% of the initial speed. For more precise tests, such as ABS or ESP algorithms optimisations mentioned here, time courses of deceleration are needed. One of the methods, relatively troublesome in terms of calculation, is the differentiation of a registered speed course. The numerical differentiation for a randomly disturbed course (Fig. 8) leads to a very unreadable form of the result, where the signal useful is hidden in the digital noise. The use of appropriate, multiple filtering is necessary. However, the result must be controlled, so that the useful information is not lost due to too strong smoothing.

In the road tests, such as the one presented in Figure 8, the following procedure proven in the practice can be applied (Origin, KyPlot or similar software):
- preliminary smoothing of the speed course with the moving average method, e.g. with ensemble average of 400 ms,
- numerical differentiation of the smoothed speed course, e.g. with the first-order method with 13 points of polynomial regression (acc. to the Savitzky-Golay method [4], [9]),
- use of the fast Fourier transform (FFT) filtering on the obtained deceleration course with 200 samples.

The effect of these actions executed on the speed course of Figure 8 is shown in Figure 9.

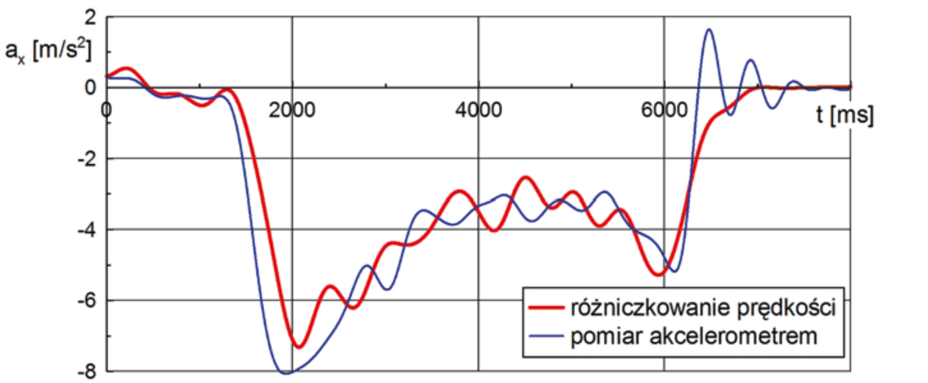

Fig. 9. Braking deceleration time courses a during the road test (see Figure 4) obtained with two methods: direct measurement with an accelerometer and differentiating speed
Legend: różniczkowanie prędkości – speed differentiation
pomiar akcelerometrem – accelerometer measurement

In addition, it presents the result of the deceleration record using the ADXL05 accelerometer [8], installed inside the coach over the centre of mass. The deceleration course was smoothed with a moving average with ensemble average of 200 ms. It was necessary because the accelerometer receives a lot of vibrations disturbing at higher frequencies, coming from the engine and the road surface. Figure 9 highlights a big difference in the received courses, as regards both the amplitude and slow-varying vibrations phase. In the final stage of braking, a significant, fading oscillation from the suspension vibrations is visible. In conclusion, you must exercise caution when using direct measurement of deceleration with an accelerometer. These sensors, cheap and with good metrology parameters, are able to record much more than it is expected in the dynamic braking testing. However, if they are improperly installed, they can introduce error both as to the size and nature of the phenomenon.

The data provided by the correlation optical sensors, despite troublesome processing, allow to obtain the deceleration courses without these defects.

5. Conclusions

The optical correlation heads parameters obtained during bench tests were compared with the data provided by the manufacturer. It was verified in this way whether the braking parameters measurements performed routinely do not conceal the danger of receiving erroneous results. The correlation optical sensors have been used for many years in most professional road tests. Their advantages: high precision, non-contact measurement, digital and analogue signal output make that their leading positions is not threatened.

The tests checking the DLS1 sensor and several other sensors of different generations executed on the presented bench (in total, five specimens were tested, in addition to three presented in the paper, including two of the latest generation: S-400 and L-350 Aqua [10]) confirmed the invariability of their parameters in time. The parameters of all the tested sensors were within the range of the accuracy guaranteed by the manufacturer. The shown deviations do not affect visibly the final testing result – which is also shown on the example. The biggest problem in the tests of the braking dynamics is reliable reproduction of the deceleration course. The direct accelerometrical methods, despite being comfortable and used in a mobile apparatus, conceal danger of receiving erroneous results resulting from e.g. incorrect fitting.

The full text of the Article is available in Polish online on the website http://archiwummotoryzacji.pl.

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