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PROBLEMS OF FIBRE OPTIC SENSOR APPLICATION IN WEIGHT-IN-MOTION (WIM) SYSTEMS

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In the present study the authors are discussing the possibility of fibre optic sensor application for weighing road vehicles in motion (WIM – weight-in-motion). The various factors affecting the accuracy of fibre optic sensors measurement are considered to be: features of the installation in the roadway, the nonlinearity and inertia of the sensor, the thermal effect, the inertial force of the vibrating vehicle and the extremely short time of the load standing on the sensor. The examples of the record signals, transferring to a fibre optic sensor, are made. The analysis of the causes of measurement error and possible ways to improve the accuracy of weighing for the solution of the pre-selection of road vehicles in motion upon the dynamic load on the axis is submitted.

Keywords: intelligent transport system, vehicle detection, weight-in-motion, fibre optic sensors, dynamic measurement, digital signal processing

1. Introduction

The growth of the level of traffic intensity in the European Union countries, the creation of the traffic control intelligent transport systems (ITS) and problems of maintaining the quality of road surfaces have led to the creation of sensor networks for weighing road vehicles. The capacitive, piezoelectric and strain gauge sensors [1], with a relatively high cost and low lifetime (10 years) are mainly used as such sensors.

In the last decade the weight fibre optic sensors, based on the change in the optical signal parameters due to optic fibre strain under the weight of a passing transport vehicle [2], have gained popularity. These sensors are more durable, they are relatively cheap in manufacture and operation. However, they are mainly used as detectors for vehicles because of the low accuracy of weight measurement (especially weight-in-motion) and high dependence on weather conditions.

In the 1990s the weighing and control of transport in motion systems using fibre optic force sensors appeared. Their usage was justified by the low cost and ease of installation on roads with heavy traffic. Fibre optic cables are placed in narrow grooves across the road and are filled with resilient rubber, transmitting the tyre pressure on the cord. The traffic flow should not be interrupted for a long time, so the ease and speed of the sensors' installation outweighed its drawback – low measurement accuracy. The tasks of weight-in-motion systems are the following [2]:

- Sorting of vehicles by type with the accumulation of statistics. This allows us to determine the traffic load and load on the road surface during the specified periods of time;
- Selection from the traffic flow of vehicles, axes of which, according to system indicated value, exceed the axle weight limit. After weighing the vehicle on more accurate scales, it is released, but it is assessed upon violation of rules.
- Transfer of the statistical data into a centralized system of transport accounting and traffic management in the region.

Analysis of current trends on WIM issues indicates that optical sensors, which are more reliable and durable in comparison with tensor and piezoelectric, are based on two main principles:

- Bragg grating (the change of diffraction in a channel under deformations)
- Change under deformations of the fibre optical properties (transparency, frequency, phase, polarization). It is the change of transparency (the intensity of the light signal) which is used in the SENSOR LINE SPT experimental sensors [5] on which these studies were carried out.

2. Operating Principles of the Fibre Optic Force Sensor

The fibre optic force sensor is a cable consisting of a photoconductive polymer fibres coated with a thin light-reflective layer (Fig. 1). A light conductor is created in this way, from which the light cannot escape. If you direct a beam of light to one end of the cable, it will come out from the other end, and in this case the cable can be twisted in any manner. It is known that such light conductors are widely used in medicine for the illumination and examination of human internal organs.

In order to measure the force acting on the cable, somehow you need to change and measure the characteristics of the light beam when the load changes. For this purpose, different technology is used, which is based on well-known principles of physics [2]:

- the phase technology with a coherent source of radiation, in this case the phase shift of the outgoing beam with respect to the incoming beam is measured
- the tunnel technology, using the physical effects, which occur when the light passes through a small hole;
- the polarization technology, measuring the change in the polarization of light in case of the light conductor geometry changing under the load;
- the spectral technology, responsive to changes in the spectral characteristics of optical path under a load;
- the amplitude technology, which measures the optical path intensity, which changes while pushing on the light conductor along its points.

At these points the deflection of a light conductor and reflective coating occurs, that is why the conditions of light reflection inside are changed, and some of it escapes. The greater the load – the less light comes from the second end of the light conductor. Therefore the sensor has the unusual characteristic for personnel, familiar with strain gauges: the greater the load – the lower the output is. Apart from the fact that it is reversed and in addition to this it is non-linear.

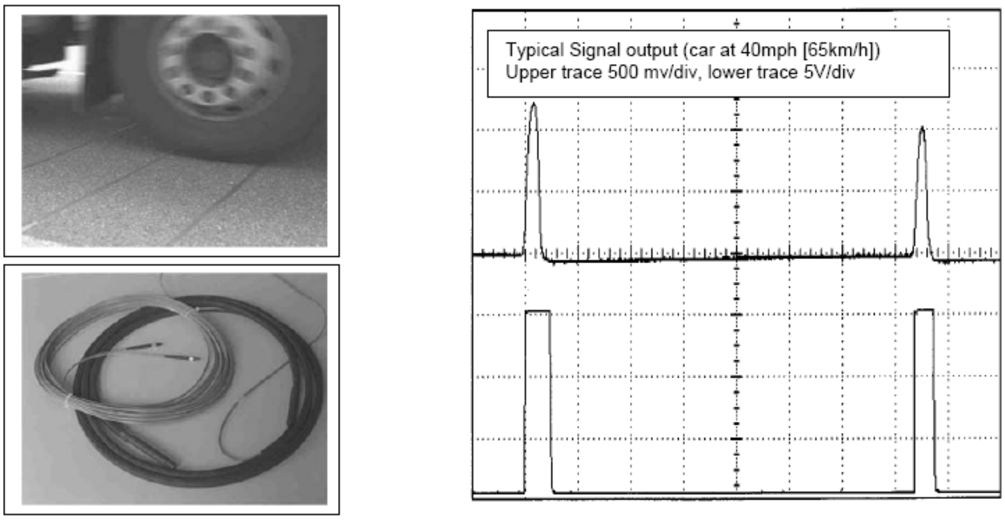

Figure 1. Location and waveform of the SENSOR LINE SPT fibre optic sensor [5]

All the aforementioned technologies, except for the last one, feature complex electronic circuits and algorithms which convert the physical effect change in the electrical signal of the required form. They are highly accurate but expensive in cost and difficult to configure and calibrate. Therefore the sophisticated technologies are not widely used in real structures. At the same time the amplitude technology is simple in the technical implementation and cheap in cost, but it has low accuracy. In the present article only the amplitude technology, which by means of using cheap microelectronics can overcome its drawbacks, while maintaining all the advantages, will be covered.

3. Sensor Output Characteristics

Load characteristic was measured from the SENSOR LINE SPT fibre optic sensor by means of a SL Transducer (optical interface) optical signal analyser developed by SensorLine GmbH [5]. The measuring length of the sensor was 49 cm, and the special instalment was made for the experiments. The optical signal analyser, which is connected to the sensor, has a transmitter and receiver of the light beam, as well as an electronic circuit which converts the change of the optical path to voltage change. The load was varied from 0 to 60 kg in a pitch of 10 kg. The results of one experiment are presented in Table 1. The data received from other experiments was similar.

Table 1. Load characteristic of the SENSOR LINE SPT [5] fibre optic sensor

Load, kg	**0.0**	**10.0**	**20.0**	**30.0**	**40.0**	**50.0**	**60.0**
Output signal, V (load)	**6.22**	**5.00**	**4.10**	**3.15**	**2.27**	**1.70**	**1.07**
Output signal, V (unload)	**6.21**	**4.73**	**3.66**	**2.90**	**2.09**	**1.58**	**1.07**

A graphic representation of the received experimental data is presented on Fig. 2, where the solid line is the load characteristic, and the dashed line is unloading characteristic. As it can be seen from the figure, the sensor has a nonlinear output characteristic and significant hysteresis, which reaches 10.7-10.9% in the middle of curve lines. A common feature of numerous data, obtained in experiments, is that as far as the load increases, the first derivate of load curve line approaches to 0, reminding an exponent by itself. Therefore the increase of the output voltage under heavy load does not make it possible to reliably distinguish one load from another:

$$\Delta U/\Delta G = k \to 0, \qquad \Delta U = \Delta G \cdot k \to 0 \tag{1}$$

Consequently, even if you use this sensor with the analyser as the threshold device in order to select the overloaded axes, one cannot guarantee it will work consistently.

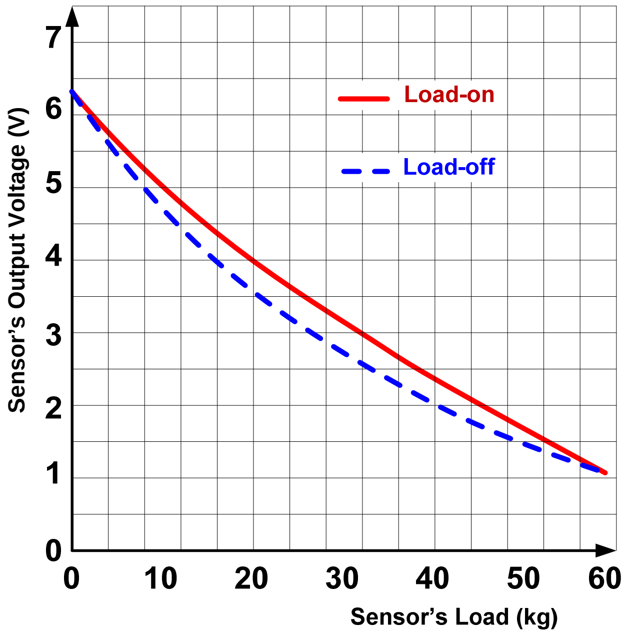

Figure 2. Output characteristic of the fibre optic sensor: solid line is the load characteristic, and the dashed line is unloading characteristic

The approximation upon the least square method of the stress sensor output $\boldsymbol{U}$ from the applied load $\boldsymbol{F}$ by the second-order polynomial during the load increment gives the following expression:

$$\boldsymbol{U(F)} = 5.642845 \cdot 10^{-4} \cdot \boldsymbol{F}^2 - 0.119143 \cdot \boldsymbol{F} + 6.19929. \tag{2}$$

Modern microelectronics, particularly the PIC-processors, make it possible to overcome this drawback and to create an optical signal analyser with a linear output characteristic. Such an analyser together with the fibre optic sensors will find use not only in vehicle weigh-in-motion systems, but also in many other spheres of industry, agriculture, medicine and everyday life. The guarantee of this is the fact that all currently existing monitors of strain gauge scales are adapted for use with strain gauge sensors having a linear characteristic of direct action: the more power – the more output. If you set a goal to replace the expensive strain gauge sensors with the cheap fibre optic sensors, the fibre optic sensors should have similar characteristics. Only this property allows fibre optic sensors to compete with strain gauge sensors and will not specify any special requirements for existing monitors. In other words, the weighing system does not have "to be aware of" the replacement of sensors.

In the overwhelming majority of applications the presence of hysteresis is not an obstacle, because the weights user is only interested in weighing the load, laid on the scales. For example, during the multi-component dosing the weight loading is gradual, with interruptions – a component by component. But as for the process of unloading, when the scales bottom is opened, nobody cares. After unloading the pause is performed, the scales are "reset" and the next weighing begins. As you can see, hysteresis does not get in the way.

The different picture can be seen in the axis weighing systems of vehicles in motion. Several axes of one vehicle or multiple axes of traffic flow can pass through the sensor in a very short period of time when the vehicle speed is high. In this case the load changes from zero to maximum values. Therefore the deformed sensor needs to recover in time before it will be crossed by the next wheel set. The ideal for this application would have been the sensor, generally with no hysteresis. The task of creating elastomeric polymer light conductor, changing the transparency under the loads, arises from that fact.

4. Principles of Weighing the Vehicle in Motion

As was mentioned above, fibre optic load-measuring cables are placed in gap across the road and are filled with resilient rubber. The gap width is 30-50 mm. Since the sensor width is smaller than the tyre footprint on the surface, the sensor takes only part of the weight axis. Two methods are used in the existing systems to calculate the total weight of the axle [1]: the Basic Method and the Area Method. The following formula is used to calculate the total weight of the axis using the Basic Method:

$$W_{ha} = A_t \cdot P_t , \tag{3}$$

where

W_{ha} – weight on half-axle,
A_t – area of the tyre footprint,
P_t – air pressure inside the tyre.

As you can see the exact values of the formula factors are unknown. The area of the tyre footprint is calculated roughly by the length of the output voltage impulse, which in its turn depends on the vehicle speed. The manufacturer's recommendations for the given vehicle type are used as pressure in the tyre.

The Area Method uses the assumption that the area under the recorded impulse curve line, in other words – the integral, characterizes the load on the axle. To calculate the integral, the curve line is approximated by the trapezoid. In this case the smaller the integral – the greater the load. This method does not require knowing the tyre pressure, but it requires the time-consuming on-site calibration. Also keep in mind that the time of the tyre passing on the sensor is too small to get an electrical signal of high quality for its further mathematical processing.

Evaluating this method and the methods of calculating the weight of vehicles in motion, one should expect very low accuracy. This is confirmed by the studies conducted at the Florida Institute of Technology (*Florida Tech*) [2]. To calculate the weight of the vehicle the Basic Method was used. The results are the following:

- front half-axle weighing errors – from –11 to +7%;
- rear half-axle weighing errors – from +8 to +36%;
- vehicle weighing error – from –1 to +18%.

If the Area Method is used, the errors turned out to be even greater: the measured and calculated weight of the vehicle was different from the real within the range from –43 to +37%.

As it turned out, the errors are highly dependent on vehicle speed and its low-frequency vibrations on the springs, in other words, on the inertial forces affected the sensor. In this regard the International Recommendation [4] contains the requirement that the road within the length of at least 30 m should be flat and horizontal before the scales approach. This reduces the vertical vibration of the vehicles and lowers the dynamic errors.

It is commonly known that the gap in the roadway is filled with resilient rubber after placing the cable in it. The resilient rubber slowly takes its original shape, so the sensor gain is lowered under frequent periodic loads.

From the aforementioned it follows that the substantial systems can only capture the moment of vehicles passage and carry out its rough sorting by class in the operating principle. The usage of fibre optic sensors in these systems is possible, but all of the aforementioned drawbacks will remain. Obviously that the firms, offering such methods, consider it permissible to put up with these drawbacks for the sake of simplicity and cheapness, not only the sensors itself but the ways of its laying on the road as well. However, to create scales with an accuracy of less than 5% the different approaches and methods are required. The obvious solution, which is devoid of the main drawbacks of the cable systems, is the platform version of the scales using the same fibre optic sensors.

It should be noted that the platform versions are also available, but they are fundamentally different from the classic design, that's why they retain the main drawbacks of the cable systems. The classic platform scales of axle weighing allow the axle to weigh, not to calculate its approximate weight. The platform width is typically less than 70 cm and is determined by the distance between the axles of the coupled suspension and tyre footprint width. It is obvious that such scales are more expensive than the cables placing in the road surface. However, the fibre optic sensors, installed in them instead of the strain gauge sensors, greatly simplify their design and reduce the cost. Furthermore, and it is more significantly, with the accurate scales on the road, the installation of expensive precision balance on the parallel road near the Point of weight control will not be required. With the help of the precision balance on the road it will be an accurate sorting and the weight of the vehicle will not be needed to retest. At the same time the highway capacity will be significantly increased, because the control scales and the queue to them will disappear. Such ideal hypothetical option is analysed in [4].

5. Discussion

The accuracy of weighing the vehicle in motion depends on many factors, but the main errors in the existing systems consist of the following: non-linearity and inertia of the sensor, thermal effects, inertial force of an oscillating vehicle and an extremely short time of the load being on the sensor. Therefore, the further improvement of the system should minimize the impact of the aforementioned factors. Possible areas might be:

- the non-linearity of characteristic can be eliminated mathematically by using PIC-processor;
- the thermal effect can be reduced by known methods of temperature compensation and periodical "zeroing" of the output signal;
- the use of platform increases the exposure time of load to the sensors, which facilitates receiving a reliable electric signal;
- the platform design also allows calculating the vehicle speed without implementation of any special sensors;
- the platform design of the scales allows testing the separation method of gravitational and inertial forces by known method used in the naval scale showing the exact weight of the cargo at the ship pitching. It may be possible to exclude the influence of the inertial forces caused by the vehicle vibrations on the spring suspension.

The aforementioned possible ways of increasing the accuracy of weighing vehicles in motion were used by the authors in the previous works and there is no doubt in their implementation and effectiveness.

While measuring the mass (weight) of vehicle in motion (Weight in Motion – WIM) the information only about the pressure, exerted by this vehicle to the sensor, laid deep into the road bed, is not enough, according to the well-known indeterminacy principle. The accuracy of weighing a vehicle in motion depends on many factors, but the main errors in the existing systems consist of the following: non-linearity and inertia of the sensor, thermal effects, inertial force of an oscillating vehicle and an extremely short time of the load being on the sensor.

At the present time fibre optic load-measuring cables are placed in gap across the road and are filled with resilient rubber. The gap width is 30-50 mm. The familiarization with the existing systems leads to the following conclusions:

- the width of the sensor is smaller than the tyre footprint on the surface, so it carries only part of the axle weight, and what is more, the tyre surface is uneven – it has a notch;
- the tyre transmission time on the sensor is too short to get an electrical signal of high quality for its further mathematical processing;
- due to the fact that the gap in the roadway after laying the cable in it is filled with resilient rubber, the sensor has a non-linearity and hysteresis. The resilient rubber slowly takes its original shape, that's why the sensor gain is changed by frequent periodic loads;
- the real system with fibre optic sensors are successfully applied only to control the traffic flow, considering that high error of weighing a vehicle in motion, namely up to 30%, makes it possible only to capture the moment of vehicles passage and carry out its rough sorting by class.

One of the solutions to solve the problem is the platform construction of the sensors instalment, which also makes it possible to calculate the vehicle speed without application of any special sensors, and the separation of gravitational and inertial forces is possible by known method used in the naval scale showing the exact weight of the cargo at the ship pitching.

At the same time, when the vehicle is in motion, the deformation of the road surface occurs, accompanied by vibrations and movement of the road surface in the horizontal plane. With high sensitivity of the sensor, the sensor responds to the deformation of the road surface earlier than the vehicle, and it will immediately put pressure on the sensor.

That's why **the second solution** is a joint information processing about the deformation of road surface and the sensor pressure makes it possible to determine (with a tolerance probability) class of the vehicle (light or freight), its speed and weight.

To register the deformation of the road surface while a vehicle is in motion, probably one may need a special way to fix the sensor in the road bed in order to increase its sensitivity to loads in the horizontal plane.

The mathematical tool for the aforementioned joint information processing about the deformation of road surface and sensor pressure is the correlation and spectral analysis of random processes treatment. The processing algorithms should use a priori data:

- about the differences of radial wheel sizes, the distances between the wheel pairs, tyre pressure, load distribution between front and rear light and freight wheel drives, etc.;
- the statistical data about the interrelation of wheel sizes, distances between wheel pairs, tyre pressure, load distribution between front and rear wheel drive of the vehicle, moving at a certain speed and the sensor response to the deformation of road surface, and also the pressure exerted by a vehicle in motion.

Such data should be obtained by the experimental and expert ways, and they should make a certain database for the application of the correlation analysis methods in solving the aforementioned tasks of determining the type of the vehicle, its speed and weight.

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