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A comparison of the properties of conditioning systems cooperating with the eddy-current inductive loop sensor

***Abstract**. The paper presents an analysis of different types of conditioning systems that are used with the inductive loop sensor. The purpose of such an analysis is to compare the quantity and the type of information obtained from the sensors and limitations of that information depending on a specific conditioning system.*

***Streszczenie.** W pracy przedstawiono analizę różnych typów układów kondycjonowania współpracujących z indukcyjnym czujnikiem pętlowym. Analiza ta ma na celu porównanie informacji pozyskiwanej z czujnika i jej ograniczenia wynikające ze stosowanego układu kondycjonowania. (**Porównanie właściwości układów kondycjonowania współpracujących z wiroprądowymi czujnikami indukcyjnymi**).*

Keywords: inductive loop sensor, conditioning system, ac-bridge, impedance, vehicle magnetic profile.
Słowa kluczowe: czujnik indukcyjny pętlowy, układ kondycjonowania, mostek zmiennoprądowy, profil magnetyczny pojazdu.

Introduction

For many years, inductive loop (IL) sensors have been used to detect vehicle presence in order to count their number, measure their length and speed and also for classification purposes [1]. The data from these sensors, which is collected over a predetermined period of time, is used to determine traffic parameters for intelligent traffic systems (ITS) [2]. A key element in measuring traffic parameters is the recognition and proper classification of vehicles. It takes place on the basis of signals obtained by IL sensor, which vary depending on the type of vehicle [3].

In the field of vehicle classification IL sensors are used in a number of ways [4, 5, 6] that largely depend on the output signal of the measurement channel, wherein the sensor is working [7]. A key element of this channel is the conditioning signal system which, apart from the sensor and the measured object (vehicle), influences the parameters of the output signal. These signals can be then used for classification purposes [4, 6]. However, it is not possible to use the signals from various systems for the same classification process. Each conditioning system with the sensor of a certain size and shape generates a subset of signals that are characteristic for its usage [5].

Many signal conditioners are used to take measurements [8-14]. One of the most popular solutions is working in the structure of the self-excitation LC-generator [9]. Information about the vehicle is contained in the frequency value of the output signal. The advantage of this arrangement is that the format of the output signal is very convenient for transmission and processing. There is no need to use any analog to digital converters.

The disadvantage is that the signal samples obtained in the measurement frequency of the output signal are low frequency. As it is known, frequency measurement requires a relatively long time. Shortening this time can result in an increase in signal frequency and thus an increase in susceptibility to external interference in real operating conditions of the IL sensor. This is largely due to the capacity distributed in the surroundings of the IL sensor and the measuring apparatus.

Less frequently used circuit is the pre-balanced AC-bridge [12]. The advantage of this solution is the possibility of obtaining samples of a signal at any sampling time that is possible to achieve from a technical point of view. The disadvantage is a more complex system structure and, in case of special applications – the price. There are also a number of special purpose, experimental solutions that are not used very often [10, 11, 14].

The output signal from the conditioning system that cooperates with the IL dedicated to measuring the traveling vehicle is known as the magnetic signature of the vehicle [8, 13]. The difficulty in comparing signals that are output by different conditioning circuits that take measurements pertaining to the same vehicle stems from the fact that each of these circuits generates a signal dependent on a different component of the impedance of the sensor or function. For the purpose of recognizing a vehicle, the most preferred system is the conditioning system which provides a separated signal that is proportional to changes in impedance components. These changes result from all the phenomena occurring in the sensor and are generated by the vehicle [15].

Phenomena occurring in the inductive loop sensor

Typically, modeling parameters of the IL sensor are used in a serial model $Z = R + jX$ (fig. 1). Two phenomena can be responsible for the changes of the measured parameters of the impedance of the sensor (both components R and X), when the vehicle is within range of the sensor [16, 17].

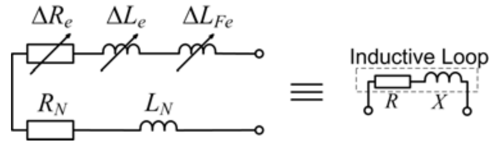

Fig.1. Equivalent circuit of the IL sensor, where ΔR_e, ΔL_e – changes in: resistance and inductance respectively, of the sensor caused by the phenomenon of eddy currents in the vehicle, ΔL_{Fe} change inductance of the sensor caused by the effect of the ferromagnetic core components of the vehicle, R_N and L_N nominal resistance and inductance

The first phenomenon is the induction of eddy currents in the metal components of the vehicle. Eddy currents produce their own magnetic flux that is directed opposite to the flow of the primary one, generated by sensor, thus weakening it. Consequently, the average value of energy stored in the magnetic field sensor is below average. The phenomenon of eddy currents results in a decrease in the value of the observed reactance ($X=\omega L$) of the IL sensor. Another result of eddy currents flowing in a metal object is above average nominal active power loss, reflected as an increase in the value of impedance component R of the IL sensor.

The second phenomenon is based on the fact that some elements of the vehicle function as a ferromagnetic core.

This leads to a local increase in the combined flux and thereby causes an increase in the average energy stored in the magnetic field. This phenomenon is observed as an increase in the measured reactance of the IL sensor over which the vehicle is moving.

Both phenomena occur simultaneously when the vehicle is moving through the IL sensor field. Depending on the shape of the chassis, components of the vehicle, its distance to the IL sensor, structure, properties of the metals, the occurrence of these phenomena can vary in intensity [7].

Methodology

Tests of various conditioning systems were conducted in laboratory conditions. Figure 2 contains a diagram of a test bench designed to test the conditioning systems. The inductive loop (IL) was permanently installed in the model road on which model of the vehicle (scale 1:15) was positioned. The IL was connected to the tested conditioning system (CSUT) by means of a transformer (Tr) used for galvanic separation (which is a standard approach). The vehicle was moved using a linear positioner. All measurements were taken in static conditions (shift-measurement-shift mode) with the moving step of the vehicle amounting to 1 mm. In each case, the position of the vehicle relative to the sensor was ±0.2 mm. The output signal (magnetic profile) of the CSUT was measured and recorded using a PC.

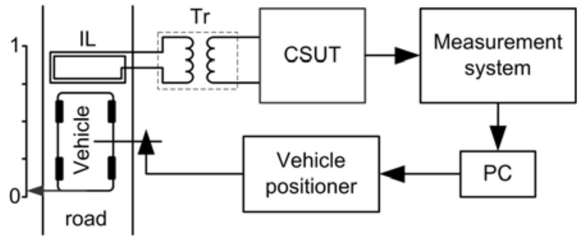

Fig.2. Test bench block diagram, where: IL – inductive loop sensor, Tr – transformer, CSUT – conditioning system under test

A LCR precision meter [18] was used to provide reference (resistance R and reactance X). The adopted research methodology involved obtaining output signals from CSUT and comparing them with the signal obtained from the reference instrument. In order to avoid the influence of frequency, all comparative tests were carried out at the same frequency of excitation signal: 49.5 kHz.

Inductive loop conditioning systems

As mentioned in the introduction, conditioning systems have been used to cooperate with the IL sensor. These systems differed in their principle of operation. The use of different systems is due to many reasons, including the price, the target application (vehicle detection, vehicle class recognition), knowledge and skill of the designers adopted in different environments.

Depending on the system used, the type of the obtained information can vary. The most desirable system is one that can provide the maximum amount of information about the vehicle. Such a conditioning system must be able to separate the changes in the impedance components from all the phenomena occurring in the sensor magnetic field. This paper presents the effect of the four types of systems cooperating with inductive loop. It highlights their advantages, disadvantages and conditions in which they operate. These systems are: LC-generator, a system based on resonance frequency, pre-balanced AC-bridge with the synchronous demodulation measurement channel and a new system that allows independent measurement of the changes in the IL impedance components.

LC-generator conditioning system

The most commonly used structure of the IL signal conditioning is a sine-wave resonance LC-generator. LC-generators can be realized based on the known structure of the main generators of Hartley, Meissner and Colpitts (Fig. 3a). Information about the measured object (vehicle) is included in the generator output frequency f_{gen}.

Figure 3b shows normalized-to-1 exemplary signals of changes in IL impedance components (R and $|X|$ obtained from a precision impedance meter [18]) and the output frequency of Colpitts oscillator.

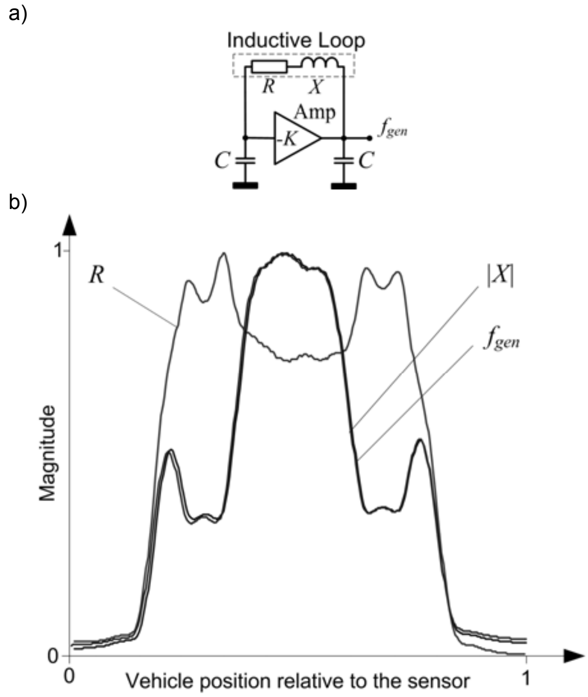

Fig.3. a) Colpitts LC-generator; b) the comparison reference signal normalized-to-1 changes in resistance R, and absolute value of changes reactance $|X|$ of IL-sensor with the f_{gen} – Colpitts oscillator output frequency signal

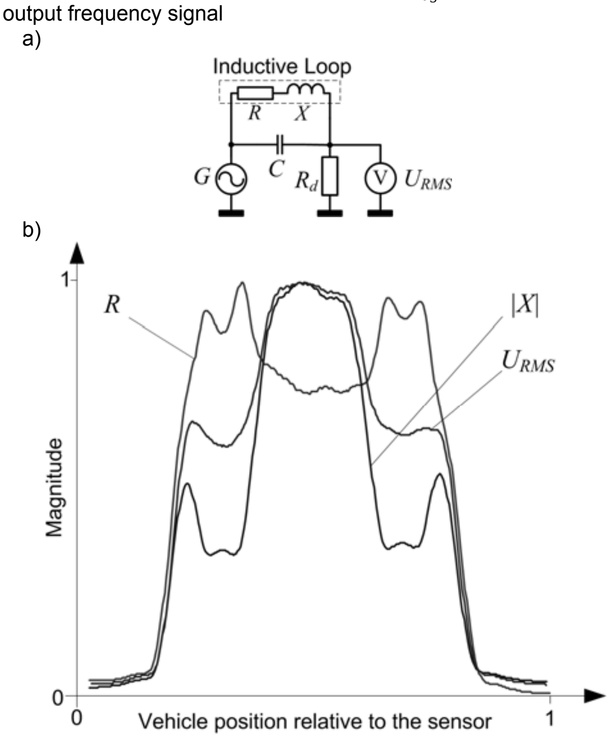

Fig.4. a) System based on resonance frequency, b) normalized-to-1 U_{RMS} signal, R and |X| - normalized-to-1 respectively resistance and absolute value of IL reactance

It can be seen that the output signal of the generator (f_{gen}) is proportional to the reactance $|X|$. The information contained in the R signal at the output of the LC-generator is lost.

System based on resonance frequency

A slightly different structure than the LC-generator system is based on a shift in resonance frequency. It is different from the LC-generator in that the resonant circuit comprising a IL is excited by an external, adjustable sine-generator. This sine-generator is usually a voltage controlled oscillator (VCO) which allows to maintain the optimal operating point of the IL conditioning system.

This point coincides with the resonant frequency. A vehicle passing in the IL sensor field shifts the resonance frequency and this causes a change in the voltage measured at the resonant circuit.

The U_{RMS} value of the measured voltage on the limitation resistor R_d (Fig. 4a) when the vehicle travels through the IL field is illustrated in Figure 4b. The parameters of the IL impedance changes measured previously are also shown. Normalized-to-1 voltage signal U_{RMS} is much different in its shape both in the signal changes in the resistance R and reactance $|X|$.

AC-Bridge base system

One of the most common conditioning systems is the pre-balanced AC-bridge base system, shown in Figure 5. It is not as popular in the applications of IL as the LC-generator, especially in detection systems where the only required information is the presence of the vehicle in the IL sensor area. Due to the nature of the inductive sensor, a Maxwell-Wien bridge is often used in a wide frequency range, as an unbalanced bridge [1, 9, 7, 12].

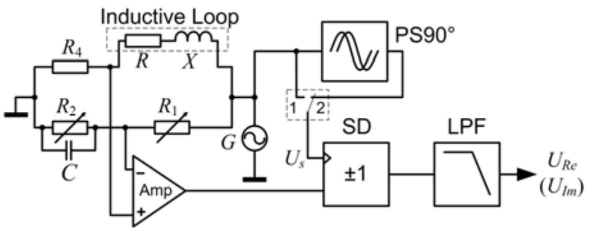

Fig.5. Conditioning system based on the Maxwell-Wien bridge, where: SD - synchronous demodulator, LPF - low-pass filter; PS90 - 90 degrees phase shifter

Assuming that the sensor is not affected by vehicle, the balance of the bridge is obtained. In the case of perfectly balanced bridge, the bridge output voltage is zero. At the moment when the vehicle appears in the area of impact IL sensor, the bridge is unbalanced and the output voltage depends on both the changes in resistance and reactance of IL sensor. If the measuring channel is synchronous demodulated, depending on the phase shift angle of voltage U_S (Fig. 5), the obtained signals are proportional to the real component or imaginary component of the output voltage of the bridge. The examples of voltage measurements after demodulation are shown in Figure 6. It presents the measurement results of voltages respectively for the 0 phase shift (U_{Re}) and 90 degrees ($|U_{Im}|$).

Experiments have also shown that the proper setting of the phase shifter allows to obtain signals similar to the R or X signal. However, the problem lies in the non-linearity of the resistance and reactance converting process to complex output voltage of the AC-bridge. This can be considered as motivation for further work on new conditioning systems.

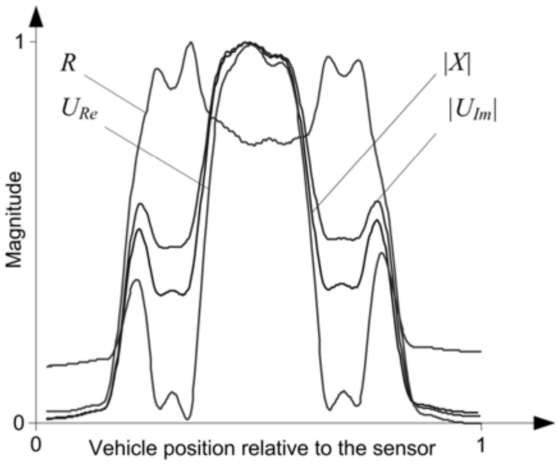

Fig.6. Normalized-to-1 the outputs of the signal conditioner, wherein the U_{Re} obtained for the position 1 of switch, the U_{Im} obtained for position 2 of switch (drawn on fig. 5)

Converter of parameters changes in inductive loop sensor impedance components to voltage signals

In [15] an analog system and method of IL signal conditioning which allows to independently measure the changes in the sensor impedance components is proposed. The idea of a conditioning system is presented in Figure 7.

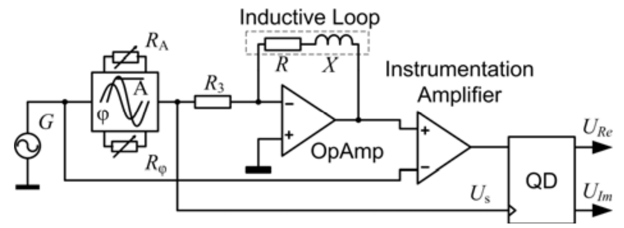

Fig.7. System block diagram of the conditioner with separate signal changes in the sensor impedance component; where QD - quadrature demodulator; R_A and R_φ are used to adjust the system balance

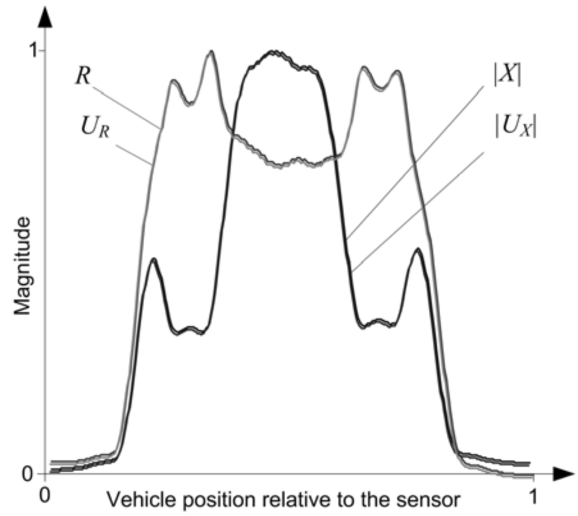

Fig.8. The quadrature demodulation output voltage signals U_R and U_X and resistance and reactance reference measurements

The system is composed of an adjusting amplitude and phase circuit, AC-current with a constant rms-value realized on an operational amplifier used to stimulate the IL sensor. The quadrature demodulator (QD) is composed of two synchronous demodulators. The signals synchronizing the demodulators have a 90-degree phase shift and are generated using the PLL method. The voltage U_s is the voltage synchronizing the quadrature demodulation process.

The presented system responds independently to both complex impedance of IL parameters and thus can increase the reliability of vehicle classification through the increase in data measured [13].

The output signals of the quadrature demodulator in the proposed system are therefore proportional to changes in the impedance components of the IL sensor.

Exemplary results of the measurements of QD output voltages are shown in Figure 8. Normalized-to-1 voltage U_R and U_X signal are proportional to the measured resistance R and reactance X of the IL sensor. These measurements were also taken using the test bench (Fig. 2).

This conditioning system has also been used for measurements in real traffic conditions [7, 13, 15].

Conclusions

This paper presents four types of conditioning signal systems that can interact with IL sensors. Each of these systems can generate so-called magnetic signature of vehicle and a generalized shape of its chassis. The magnetic signature of the signal allows to implement these systems in vehicle classification systems, because its shape is characteristic to the type of vehicle. It was shown that the signals obtained using each of the systems are in different ways dependent on the parameter changes in the impedance of the IL sensor.

This paper presents different types of systems built by the authors, but also used in research and commercial applications. It shows the signals obtained from these systems, compared with reference signals obtained from an impedance meter. These comparisons illustrate a difference between the signals and the reference signals both in shape and number.

The paper presents a new method of measuring independent parameter changes of the impedance of IL sensor which uses an electronic system.

Only by converting impedance component changes to voltage affords to obtain the maximum amount of information from that process. Thanks to this, the authors can hope that the use of this system will improve the quality of classifying vehicles which the authors intend to take up in the next stage.

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REFERENCES

[1] Gajda J., Sroka R., Stencel M., Burnos P., Zeglen T., Piwowar P., Marszalek Z.: Measurement of road traffic parameters, Publishing house PWN, Warsaw (2015), (in Polish)

[2] Klein L. A., Sensor Technologies and Data Requirements for ITS, Artech House (2001)

[3] Gajda J., Sroka R., Stencel M., Zeglen T., Wajda A., A vehicle classification based on inductive loop detectors, *in Proceedings of the 18th IEEE Instrumentation and Measurement Technology Conference*, Budapest (2001), 460-464

[4] Gajda J., Stencel M., Highly selective vehicle classification utilizing dual-loop inductive detector, *Metrology and Measurement Systems*, 21 (2014), no. 3, 473–484

[5] Klein L. A., Mills M.K., Gibson D.R.P., Traffic Detector Handbook, Third Edition, *Raport no. FHWA-HRT-06-108*, 1 (2006).

[6] Gajda J., Mielczarek M., Automatic vehicle classification in systems with single inductive loop detector, *Metrology and Measurement Systems*, 21 (2014), no. 4, 619–630

[7] Marszalek Z., Analysis of metrological properties of vehicle axle detection systems with inductive loop sensors, *PhD. Dissertation, AGH University of Science and Technology*, (2013), (in Polish)

[8] Ali S.S.M., George B., Vanajakshi L., An Efficient Multiple-Loop Sensor Configuration Applicable for Undisciplined Traffic. *IEEE Transaction on Intelligent Transportation Systems,* 14 (2013), no. 3, 1151-1161

[9] Anderson R. L., Electromagnetic Loop Vehicle Detectors, *IEEE Trans. on Veh. Technol*., 19 (1970), no. 1, 23-70

[10] Ali S.S.M., George B., Vanajakshi L., Venkatraman J., A Multiple Inductive Loop Vehicle Detection System for Heterogeneous and Lane-Less Traffic, *IEEE Transaction on Instrumentation and Measurement*, 61 (2012), no. 5, 1353-1360

[11] Marszalek Z., Sroka R., Stencel M., A new method of inductive sensor impedance measurement applied to the identification of vehicle parameters, *Metrology and Measurement Systems*, 18 (2011), no.1, 69-76

[12] Gajda J., Piwowar P., Sroka R., Stencel M., Zeglen T., Application of Inductive Loops as Wheel Detectors, *Transportation Research Part C: Emerging Technologies*, (2012), 57-66

[13] Marszalek Z., Sroka R., Zeglen T., Inductive loop for vehicle axle detection from first concepts to the system based on changes in the sensor impedance components, *in Proceedings of 20th International Conference on Methods and Models in Automation and Robotics*: 24–27 August 2015. Miedzyzdroje, Poland, (2015), 765-769

[14] Burnos P., Gajda J., Marszalek Z., Piwowar P., Sroka R., Stencel M., Zeglen T., Road traffic parameters measuring system with variable structure, *Metrology and Measurement Systems*, 18 (2011), no. 4, 659-666

[15] Zeglen T., Simulation and experiment verification of inductance sensor interfacing circuit for metallic object detection, *in Proceedings of XVIII Symposium: Modelling and Simulation of Measurement Systems*, Krynica (2011), 49-57, (in Polish)

[16] Mills M.K., Self inductance formulas for multi-turn rectangular loops used with vehicle detectors, *33rd IEEE Vehicular Technology Conference*, (1983), 65-73

[17] Marszalek Z., Field model of inductive loop sensor, *in Proceedings of XVIII Symposium: Modelling and Simulation of Measurement Systems,* Krynica (2011), 19-26, (in Polish)

[18] Agilent E4980A 20Hz - 2 MHz Precision LCR Meter