VERIFICATION OF SENSORS FOR YAW RATE AND LATERAL ACCELERATION IN CAR ESP SYSTEM

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Abstract

This study analyzed the possibilities to validate the indications of sensors for yaw rate and lateral acceleration within the scope of extended diagnostic routine of the car ESP system at Vehicle Inspection Stations. The stand tests were performed using the reference sensors and a standard diagnostic tester. The comparison of the yaw rate and lateral acceleration results obtained from the working sensor under examination, recorded with the Vbox unit, and the results from the reference sensor demonstrated a good conformity both in quality and quantity. But these tests demonstrated also a pure conformity (both in quality and quantity) with runs obtained from tester. The Root Mean Square (RMS) was used as factor of qualitative estimation. These inconveniences were caused by in sampling frequency incompatibility and lack of recording synchronization for signals from the tester and from reference sensors. The question of primary importance is a firmware modification for selected testers. Such a tester should be able to record signals from a reference sensor and have a set sampling frequency for signals from a working sensor. On the basis of already carried out research analyses the suggested frequency should be no lower than approximately 10 Hz. It resulted from a spectral analysis carried out for possessed runs maintaining the Nyquist limit frequency.

Keywords: yaw rate; lateral acceleration; operating sensor; reference sensor; diagnostic tester

1. Introduction

A proper operation of the ESP system requires signals obtained from many sensors; among others from the sensors of lateral acceleration a_y and yaw rate $d\psi/dt$. In the modern ABS/ESP systems these parameters as well as other parameters are measured with the integrated MEMS type sensors. These sensors are subject to an active on-board diagnosis [3, 5-7]. With diagnostic testers only failure of these sensors can be read and low-precise time runs of their signals can be recorded also. The failure codes mainly refer to electrical type failures.

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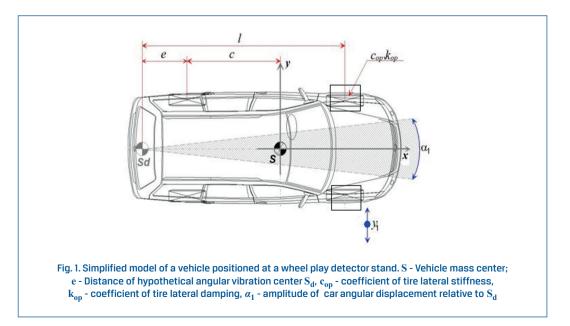
Following the analysis of tester software one may state the fact, that there are no checking procedures for verifying indications of discussed sensors and the performed tests are relevant to their operating activity only.

The focus of studies on preparation of such verification procedures should be as follows:

a) Preparation or supplementation or extension of the tester internal programs which enable the indication accuracy of ESP sensors to be evaluated in relation to the reference sensor indications and then the estimation if the accuracy is suitable for a proper operation of the ESP system;

b) Within the framework of the previous item "a" establishing a sampling frequency for signals received by the diagnostic tester from operating sensors and synchronizing them with signals from reference sensors to enable a qualitative analysis by comparison of their runs; and then establishing the quantitive evaluation coefficient, similarly as it is for evaluation of brakes or shock absorbers;

c) As the further extension of item "b", as before, establishing the evaluation coefficient both for yaw rate and lateral acceleration for the appearance of sideslip angle limiting value which should initiate reaction of the ESP system.

Such a test, according to studies conducted by the research team from the Institute of Automotive Vehicles and Combustion Engines, Cracow University of Technology [7] could be performed at a diagnostic line using plate stand (a wheel play detector unit), where a given repeatable plate excitation is executed with the axle wheels of vehicle's front or rear set up on detection plates.

In the much studies a simplified, dynamic, two-dimensional model of a vehicle was applied to its position at the wheel play detector stand, Figure 1.

Fig. 1. Simplified model of a vehicle positioned at a wheel play detector stand. S - Vehicle mass center; e - Distance of hypothetical angular vibration center S_d, c_{op} - coefficient of tire lateral stiffness, k_{op} - coefficient of tire lateral damping, α_1 - amplitude of car angular displacement relative to S_d

On the basis of experimental study it was demonstrated that within a lateral movement range of wheel play detector plates (about of 100 mm) it could be assumed that a vibration center S_d is located at the rear axle of vehicle. In the author's study the factor analysis was carried out to analyze influences of selected vehicle parameters (i.e., stiffness and lateral damping in tires, wheelbase, and moment of inertia round coordinate axes of vehicle) on angular vibration runs.

2. Experimental studies

In many modern cars the lateral acceleration and yaw velocity sensors are located in the ABS controller. A location of the ABS controller/module occurs in a different places and generally most often it is localized in a motor compartment close to a collision bulkhead. The sensor's location determines a vehicle position at the test stand enabling a convenient results processing and analyzing.

For the test purposes a VW Passat car was used. In this car, the integrated sensor (a_y, dψ/dt) is placed underneath a single piece rear seat in a hollow of floor panel (see Figure 2). The vertical plane of sensor symmetry is in line of a vehicle plane.

Fig. 2. Measuring apparatus located inside a tested car. The reference sensor – six-parameters measuring IMU block of Vbox 3i unit, RACELOGIC. The arrow points the operating sensor location underneath a rear seat. Upper part of this figure presents an apparatus set: IMU and operating sensor in real position during measurement. Pointed line is auxiliary only

For this car the stand and road tests were performed.

2.1 Road tests

The road tests were auxiliary tests for this study. Since the sensor manufacturer did not publish its scale factors neither for lateral acceleration nor for yaw rate, they had to be defined in experimental way. Due to this the scope of road tests included the followings:

a) Steady state circular test [10] with constant radius and discrete test speed;

b) Checking the reaction for continuous sinusoidal test [11]; in order to verify the meas-ured values by comparison of them and the runs taken by a reference sensor.

In order to establish the values enabling the scale factors to be determined, the steady state circular test was performed with a constant radius r = 14.5 m as for a right and left turn test. During tests a linear speed was measured and recorded at the point located at 0.96 m above the IMU transducer (the antenna of GPS Vbox 3i RACELOGIC unit was installed on the car roof). Also, the components of angular velocity vector (i.e., roll velocity $d\varphi/dt$, pitch velocity $d\xi/dt$, and yaw velocity $d\psi/dt$), as well as acceleration vectors (a_x, a_y, a_z) were measured at the point considered to be a center of orthogonal coordinate system for the IMU measuring block. The electric voltage signals a_y and $d\psi/dt$ of the operating sen-sors were measured as well.

For effective determination of such scale factors, the simplified, two-dimensional model was adopted (a similar one as was demonstrated in Figure 1); and experimental studies were performed at low speeds 10 km/h, 15 km/h and 20 km/h to minimize rolls and tilts (to make them possibly negligible in analyses).

Having the values of velocity "v" [m/s] and radius "r" [m] the yaw velocity $d\psi/dt$, [rad/s] which are measured by the sensor could be determined with a commonly known general mechanics formula:

$$v = \left(\frac{d\psi}{dt}\right)\cdot r \tag{1}$$

from where:

$$\left(\frac{d\psi}{dt}\right) = \frac{v}{r} \tag{2}$$

v – velocity of vehicle, m/s

ψ – yaw rate of vehicle, rad/s

r – radius of vehicle mass center circular path, m.

And then, with adopted simplifications it could be assumed that a lateral acceleration is close to a centripetal acceleration ay (see e.g., [13]); and therefore:

$$a_y \approx \frac{v^2}{r} \tag{3}$$

In Table 1 the values needed for scale factors determination are summarized.

Tab. 1. Summary of values to determine a scale factor for operating ESP sensors

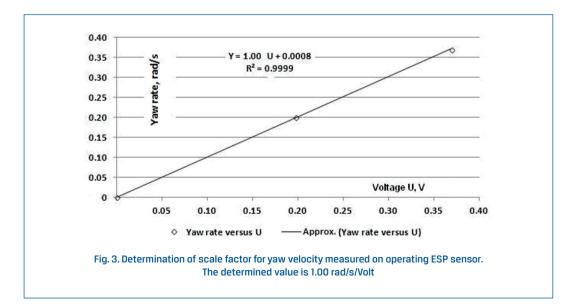| v km/h m/s	σ_v m/s	r m	σ_r m	(dψ/dt) Volt	(dψ/dt) rad/s Formula (2)	a_y Volt	a_y m/s/s Formula (3)
10		14.37	0.41				
2.92	0.05			0.20	0.20	0.11	0.60
15		14.44	0.34				
4.33	0.07			0.30	0.31	0.19	1.30
20		14.45	0.25				
5.38	0.03			0.37	0.38	0.26	2.00
25		14.64	0.18				
6.92	0.07			0.41	0.47	0.32	3.18

In Figure 3 and Figure 4 the corresponding graphs are demonstrated, which enabled the demandable scale factors to be determined. On the basis of these graphs, the scale factor of yaw velocity is:
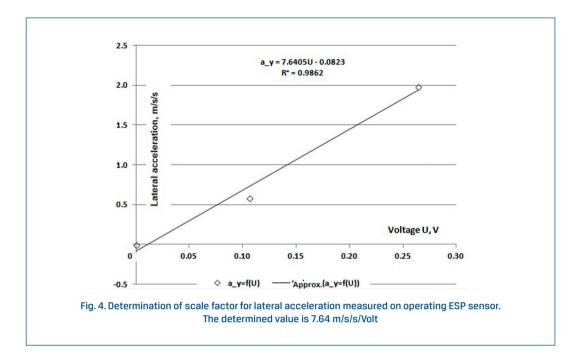
$$k_{(d\psi/dt)} = 1.0 \text{ rad/s/V} = 57.4 \text{ deg/s/V}$$

and accordingly, the scale factor of lateral acceleration is:
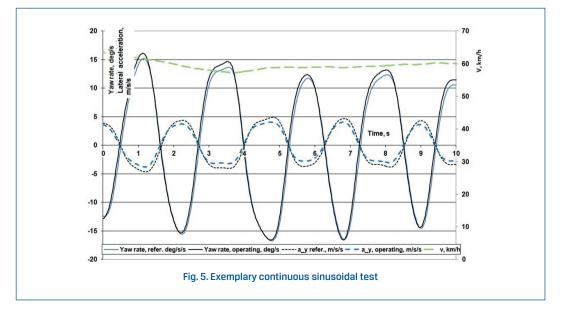
$$k_{a\_y} = 7.64 \text{ m/s/s/V}$$

therefore, an average error per square root of linear approximations is very small, and related to it the coefficient of determination $R^2 = 0.9862$

Fig. 3. Determination of scale factor for yaw velocity measured on operating ESP sensor. The determined value is 1.00 rad/s/Volt

Fig. 4. Determination of scale factor for lateral acceleration measured on operating ESP sensor. The determined value is 7.64 m/s/s/Volt
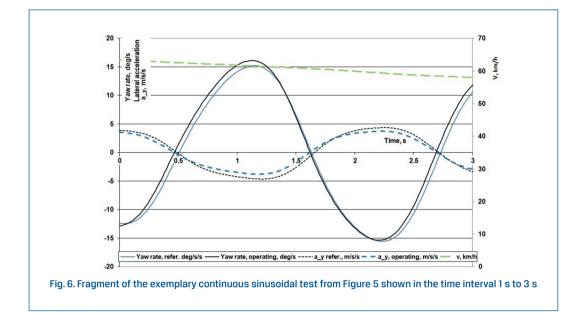
Subsequently, the road tests were performed with a continuous near-sinusoidal test at frequency of about 0.5 Hz and amplitude $\pm\pi/4$ rad, and at speeds of about 60 km/h. Exemplary road test shows

Figure 5 and Figure 6.

Fig. 5. Exemplary continuous sinusoidal test

Fig. 6. Fragment of the exemplary continuous sinusoidal test from Figure 5 shown in the time interval 1 s to 3 s

For the evaluation of obtained results, the differences between extrema as well as the maximum of absolute difference of all values were adopted.

The maximum differences between extrema of particular parameters measured from the reference and operating sensors ESP are as follows:

- **for yaw rate: 1.997 deg/s**
- **for lateral acceleration: 1.01 m/s/s**

Tab. 2. Extrema of determined parameters

$(d\psi/dt)_{ESP}$ deg/s	16.2	-15.3	14.6	-16.5	12.3	-16.2	13,1	-14.3	11.4
$(d\psi/dt)_{ref}$ deg/s	15.2	-15.4	13.7	-16.3	12.2	-16.1	12.4	-14.3	10.6
Difference to reference value %	7.0	0.6	7.0	1.0	0.8	0.6	6.0	0.0	**8.0**
$a_{y, ESP}$ m/s/s	-3.8	3.7	-3.1	4.1	-2.8	4.1	-3.0	3.6	-2.8
$a_{y, ref}$ m/s/s	-4.6	4.3	-3.9	4.9	-3.7	4.7	-3.8	4.3	-3.4
Difference to reference value %	20.0	15.0	20	16.0	**24.0**	13.0	21.0	16.0	18.0

Index „ESP" is placed for a parameter value from operating sensor

Conclusions from road tests

- The runs of a_y and $d\psi/dt$ signals from ESP sensor calculated on the basis of scale factors with the above described method gave the curves close to reference signals and can be used in the further measurements. Mainly it refers to the yaw velocity.
- The extrema differences summarized in Table 2 are much higher for the lateral acceleration (in relation to reference values even by 24%). The frequency of continuous sinusoidal tests was of about 0.5 Hz at the amplitude (a steering wheel rotation angle) $\pm\pi/4$ rad.
- In future research the influence of the amplitude mentioned above, frequency and velocity should be studied, especially in the case of lateral acceleration.

2.2 Stand tests

For this study the stand tests were performed as well. For measurement and recording the same measuring apparatus was used as for before mentioned road tests supplemented with a standard diagnostic tester CDIF 3 and a draw-wire encoder for measuring plate movements.

The rear wheels of a car were placed at rotary and sliding plates. The front wheels were locked with wedges. The lateral plate excitation was realized manually with the amplitude about of ± 20 mm and frequency of about 0.5 Hz. The plate movements were recorded by means of draw-wire resistance encoder; a component part of the test stand is shown in Figure 7.

The measured parameters, except the data from tester, were recorded with the Vbox unit.
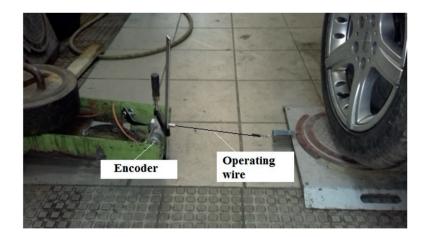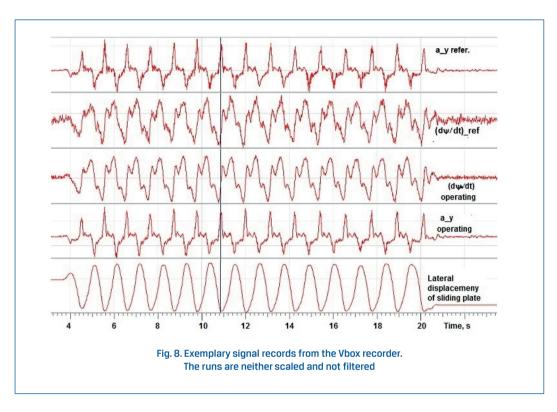

Fig. 7. View of a component part of the test stand. Rear wheels of vehicle are placed on rotary and sliding plates. The picture shows a draw-wire encoder connected with the plate under the left wheel of vehicle
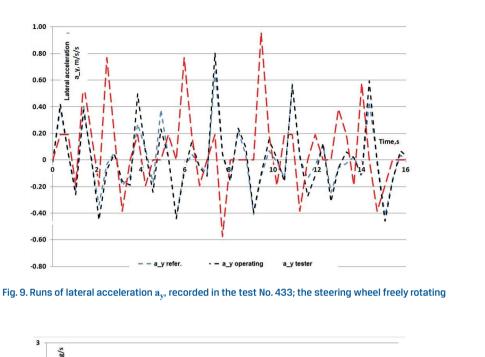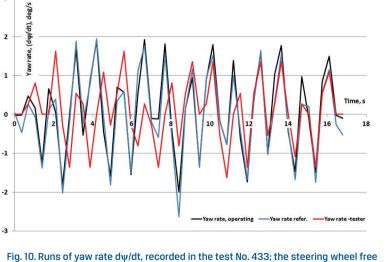
In Figure 8 the signal runs from the Vbox 3i recorder are shown in Volts.

Fig. 8. Exemplary signal records from the Vbox recorder.
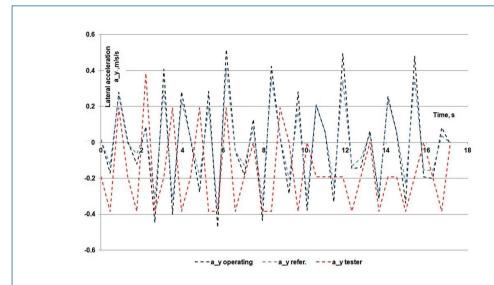The runs are neither scaled and not filtered

The sampling frequency of the tester is on average, 2.5 Hz.

During the course of results processing the runs from the tester were "manually" synchronized with the runs from the Vbox recorder. With the program presented in [15], after scaling and filtration of the signals from the Vbox recorder, the samples were recorded with a step corresponding, approximately, with the tester sampling (its sampling step is 0.35 s).
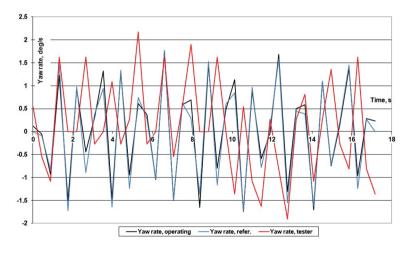
The graphs on the following pages show the time runs of analyzed values, as an instance for three tests at the test stand.
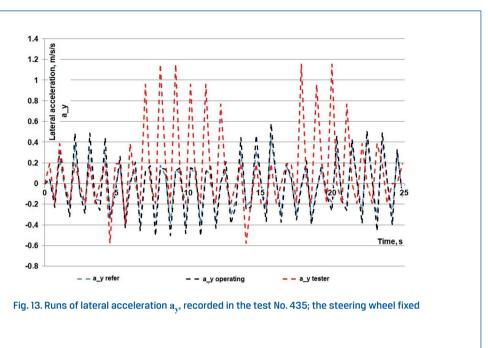
Fig. 9. Runs of lateral acceleration a_y, recorded in the test No. 433; the steering wheel freely rotating

Fig. 10. Runs of yaw rate $d\psi/dt$, recorded in the test No. 433; the steering wheel free

Fig. 11. Runs of lateral acceleration a_y, recorded in the test No. 434; the steering wheel fixed

Fig. 12. Runs of yaw rate $d\psi/dt$, recorded in the test No. 434; the steering wheel fixed

Fig. 13. Runs of lateral acceleration a_y, recorded in the test No. 435; the steering wheel fixed

Fig. 14. Runs of yaw rate $d\psi/dt$, recorded in the test No. 435; the steering wheel fixed
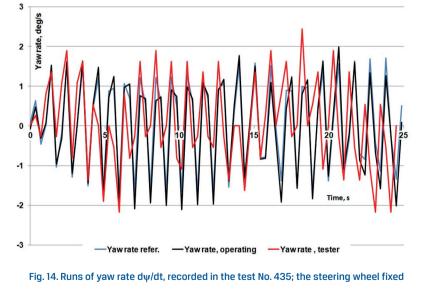
The runs shown in Figures 9 to 14 are accordingly originated from:

- Operating ESP sensor;
- reference sensor (the IMU RSCELOGIC measuring block);
- tester CDIF 3, after synchronization.

The sampling period, averaging in the runs from the tester, was 0.35 s. This period was "synchronized manually" with the sampling period of reference runs 0.01 s, recorded during trials (for this processing every 35 sample was taken).

As the quantitative evaluation coefficient for suitable runs, the RMS value was adopted, determined with a commonly known formula (see e.g. [1], [2] and[13]):

$$RMS_q = \sqrt{\frac{1}{T} \int_0^T q^2(t) \, dt} \tag{4}$$

where: $q(t)$ is evaluated quantity; T - averaging time.

For the runs shown in Figures from 10 to 15 the calculated RSM values are presented in Table 3.

Tab. 3. The RMS values for analyzed runs

RMS for Trial No.	a_y, m/s/s			$d\psi/dt$, deg/s		
	ESP	Ref	Tester	ESP	Ref	Tester
433	0.23	0.26	0.30	1.11	1.12	**0.84**
434	0.29	0.22	0.27	1.02	1.13	1.02
435	0.35	0.27	**0.43**	1.20	1.23	1.15

Conclusions from stand tests

- The comparison of the yaw rate and lateral acceleration results obtained from the working sensor under examination, recorded with the Vbox unit, and the results from the reference sensor demonstrated a good conformity both in quality and quantity.
- RMS values calculated on the basis of results recorded directly with the ESP working sensor are close to the RMS values calculated from the results obtained with the reference (standard) sensor. This means that the proposed method of excitation of vibrations to assess the operation of sensors ay and dψ/dt can be used in diagnostic practice. It lets you compare the performance of an ESP sensor with a reference one.
- RMS values calculated on the basis of tester results differ from others. Accuracy of registration and evaluation of yaw rate and lateral acceleration with a scan tool requires an increase in signal sampling frequency. This applies to both qualitative and quantitative assessment, expressed by the adopted quantitative evaluation coefficient, i.e., the run root-mean-square value (RMS).
- For purposes of the extended diagnostic routine of the ESP systems, the sensor manufacturers should publish its scale factors at least for lateral acceleration and for yaw rate; and car manufacturers should precisely define a localization of this device.

3. Conclusions

The analysis of obtained results carried out and directions of further research.

This paper presented possibilities and inconveniences in the extended diagnostic routine performance of the car ESP system at Vehicle Inspection Stations (SKP) using the standard testers.

In summary, the following remarks and requirements can be concluded:

1) The verification of the lateral acceleration and yaw rate sensors can be done with the comparative measurements using reference sensors of higher class than working sensors. The reference sensors can be placed in the vicinity of working sensors, e.g., fixed in adjustable holders, adjustable suction holders, etc.

2) In view of the accuracy of lateral acceleration measurement, location of such sensors should be within a radius of a few centimeters in relation to the center point of working sensor. Such requirements (as to a distance to a vehicle mass center) are set by the manufacturers of lateral acceleration sensors used for measurements defining lateral dynamics of vehicles (see, e.g., [10], [11]). Under conditions of SKP that procedure is inconvenient because it demands adequate data to be entered into the tester software (the entries of sensor location coordinates related to the vehicle mass center) and would complicate the diagnostic work.

3) The measurement of yaw rate is unequivocal. As is known, the angular velocity vector is a free vector and as such it does not need an anchor point. It is important to have the axis of reference sensor set in parallel with a vertical axis of vehicle, and this is possible to be set with an appropriate positioning of the sensor. The primary importance question is a firmware modification for selected testers. Such a tester should be able to record signals from a reference sensor and have a set sampling frequency for signals from a working sensor. On the basis of already carried out research analyses the suggested frequency should be no lower than about of 10 Hz. It resulted from a spectral analysis carried out for possessed runs maintaining the Nyquist limit frequency [1, 2].

4) A quantitive assessment coefficient for ESP sensor could be the effective value RMS, which is widely applicable in many other disciplines for evaluation of periodical runs [2].

5) Some, minimum, requirements are also addressed to car manufacturers. For purposes of extended diagnosis they should publish a location of sensors for lateral acceleration and for yaw rate in a specific car as well as the sensor scale factors. Without this important piece of information the validation of these sensor indications, at SKP level, would be difficult (it requires additional road test to be performed in order to establish experimentally the scale factors; as it is described in Section 2).

6) Under conditions of Vehicle Inspection Stations, i.e., on the basis of stand tests, the evaluation of sideslip angle limiting value at which the ESP system should be activated is not possible. This issue should be the subject of separate research.

4. Acknowledgement

5. Nomenclature

a_y lateral acceleration of vehicle – a component of vehicle mass center acceleration vector in the direction of the axis Y, [16]

$\frac{d\psi}{dt}$ yaw rate (yaw velocity) – yaw angle derivative ψ, referred to time – a component of vehicle angular velocity vector in the direction of Z axis, [16]

RMS   Root Mean Square – the signal root-mean-square value

U   electrical voltage

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