A METHOD FOR THE ESTIMATION OF SIDESLIP ANGLE FOR A VEHICLE EQUIPPED WITH A ONE-ANTENNA GPS MEASURING SYSTEM FOR STEADY STATE MOVEMENT

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Abstract

One-antenna GPS systems present no possibility for the direct determination of vehicle slip angle. This is an easy task for dual antenna systems; however, many users have this kind of apparatus. In this paper, a method of estimation of this parameter, which is important for the estimation of vehicle stability and road-holding ability factors, is proposed (e.g. TB factor calculated on the basis of data from input test [9]). The method is based on two parameters measured by a one-antenna GPS system; these are the heading angle created from the Doppler channel coming directly from the GPS engine, and the yaw rate measured by an IMU device integrated and cooperating with the GPS engine. The sideslip angle which was calculated according to the proposed method is compared with an equivalent angle calculated on the basis of data from a non-slip measurement of velocity components for selected point of vehicle acquired using. The presented method is illustrated with examples from real road tests. In the author's opinion, the sideslip angle calculated with the application of measurement data obtained from a one-antenna GPS device could be used in practice. From comparison with another upper mentioned method that the differences between average values of sideslip angles obtained from both considered methods is not greater than 8%.

Keywords: Sideslip angle, heading angle, yaw angle, yaw rate, GPS receiver signals

1. Introduction

One-antenna GPS systems present no possibility for the direct determination of vehicle slip angle. As is widely known, this is not a problem in the case of dual antenna systems [1], [3], [4]; however, one-antenna systems are used in many laboratories and research centres. It would be useful to identify any method for the calculation of this important parameter, which is one of the important factors with regard to lateral dynamics of automobiles not least because it is a requirement of the TB formula for RSV/ESV vehicles, where T is the

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yaw rate response time to its firs maximum and B is the sideslip angle in the steady state part of the step input test [9].

In this paper, a method of estimating this important parameter is proposed. This method is based on two quantities measured by one-antenna GPS system: the heading derived from the Doppler channel coming directly from the GPS engine, and the yaw rate measured by an IMU device cooperated with the GPS engine.

The proposed method is addressed to researchers which experimentally tested (on the road) stability and road-holding ability of automobiles (testing prototype, comparing properties actual manufactured (series) automobiles after chassis modification or in frame research work realised by research and developing centres, universities etc), according to ISO 4138 [10], ISO 7401[9], ISO 3888, GOST-R 52302 [6], RSV/ESV Requirements [16]. This method was not addressed directly for designers of on-board systems which enhance active safety of vehicle (i.e. electronic stability control –ESC). Please see [2], which contains extended review of literature connected with this problem).

2. A short description of the proposed method

In [8] a diagram defining the set of vehicle angles during a vehicle left turn is presented (see Figure. 1).

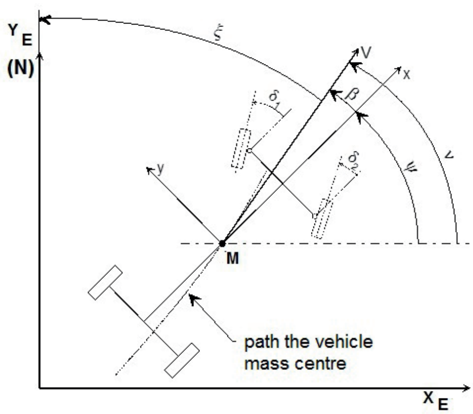

Fig. 1. Diagram of a vehicle flat model with characteristic angles in the X_E, Y_E Earth fixed axis system, **M** – mass centre, **V** – velocity vector, ψ – yaw angle, β – sideslip angle, ξ – heading angle, δ_1,δ_2 – front wheels steer angles, ν = ψ+β – course angle according to [14]

If Y_E will be directed to North (N) than the following expression may be written in accordance with Figure. 1:

$$\psi + \beta + \xi = n \cdot (\pi/4), \quad n=1...4 \tag{1}$$

After differentiating (1) [5], in the time domain will be:

$$\frac{d\beta}{dt} = -(\frac{d\psi}{dt} + \frac{d\xi}{dt}) \quad (2)$$

The sideslip angle β will be obtained after integration formula (2) in define time period.

$$\beta = \int_{t_1}^{t_2} \left[-\left(\frac{d\psi}{dt} + \frac{d\xi}{dt}\right)\right] dt \quad (3)$$

Heading angle (ξ) [18] is a Doppler derived channel coming directly from GPS engine. This heading will be 'course over ground' bearing at the antenna location with respect to North, irrespective of vehicle direction. If IMU integration is on speed will filtered using Kalman filter producing a more noise free channel that is also lever arm compensated to remove body pitch and roll induced overshoot during high dynamic manoeuvres. In the case that the GPS signal is lost the IMU will continue to provide heading data however this degrade in accuracy over time. It is recommended not to use data that has been without GPS for more than 10 seconds.

Yaw Rate (ψ) [18] is measured directly with IMU help the yaw plane of vehicle.

The effective calculation of sideslip angle will be presented as an example.

3. Demonstration of the calculation of sideslip angle according to the proposed method

A medium-sized car was tested. The flat model presented in Figure. 2 is considered.

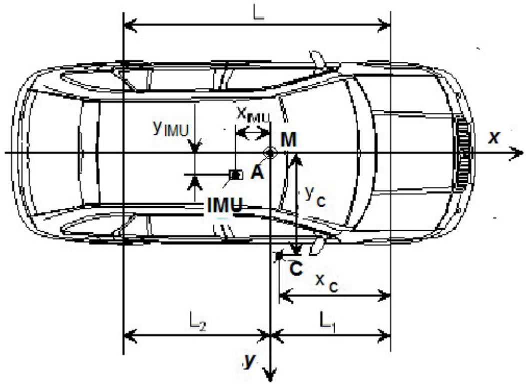

Fig. 2. Diagram of the tested car in projection to (XE ,YE) plane: **M** – mass centre; **C** – optical centre of two parameters Correvit S-CE sensor for non slip velocity components measurement (longitudinal V_L and lateral V_Q); IMU inertial measurement unit cooperating with the GPS system; **L** – wheel base; L_1 – distance of car mass centre from front axle; L_2 – distance of car mass centre from rear axle; x_C, y_C – coordinates of S-CE sensor optical centre (it is centre of light spot which is emited on the road from Correvit sensor) in vehicle axis system; x_{IMU}, y_{IMU} – coordinates of IMU centre. Antenna A should be placed as close as mass centre M.

A vehicle with a left-hand type axis system was used. It is analogical as for IMU measuring block cooperating with the applied GPS (Vbox3i Racelogic model device) [19] (see Figure. 3).

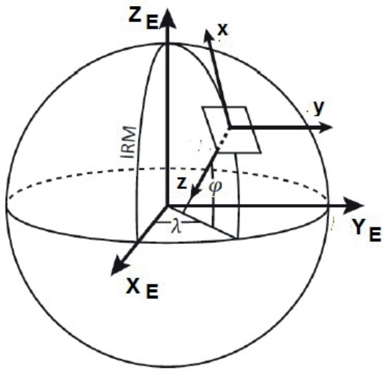

Fig. 3a. The general Earth coordinate system use for measurement with GPS and vehicle coordinate system [3], [19], according to International Earth and Rotation and Reference System Service (IERS). Through IRM the International Reference Meridian is marked.

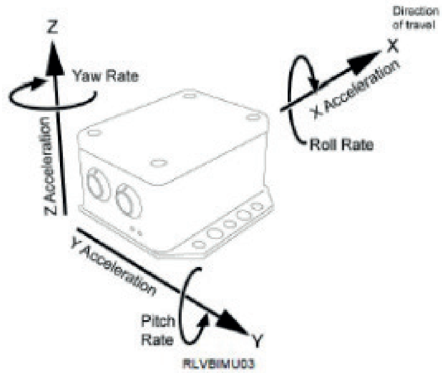

Fig. 3b. Six-parameter IMU measuring block coordinate system [19].

The main data of the tested car which is important with regard to the processing of test results is presented in Table 1 (also see Figure. 1).

Tab. 1. Selected data of the tested car

Mass during tests, kg	Wheel base L, m	L_1 m	L_2 m	x_C m	y_C m	x_{IMU} m	y_{IMU} m
1340	2.462	1.102	1.360	1.030	1.0	-0.320	0.200

The car was equipped with 185/60 R14 winter tyres. Inflation pressure for front and rear wheels was 0.2 MPa.

The left turns were executed in a test frame at an arbitrary speed of 50 km/h. The car was initially driven in a straight line and was then gradually turned to an approximate steering-wheel angle of 45±5 degrees. It is appropriate to stress that this was not a step input test.

Raw data produced through a series of test runs is presented in Figure. 4.

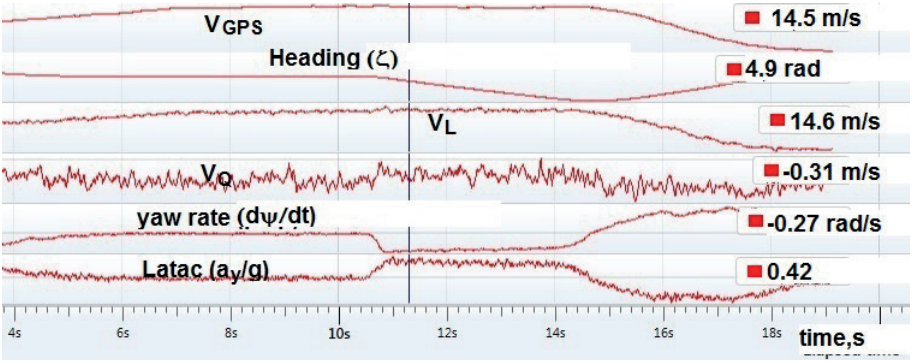

Fig. 4. Runs to obtained raw data measured and registered in the Vbox device [20]. The parts of the runs in section placed between from 4 s to14 s is taken in account to further analysis. A worth of parameters which are listed on the right corresponds to a time moment 11,2 s.

The runs from Figure. 4 after preliminary processing [23] (qualification, scaling, filtering etc.) are presented in Figure. 5.

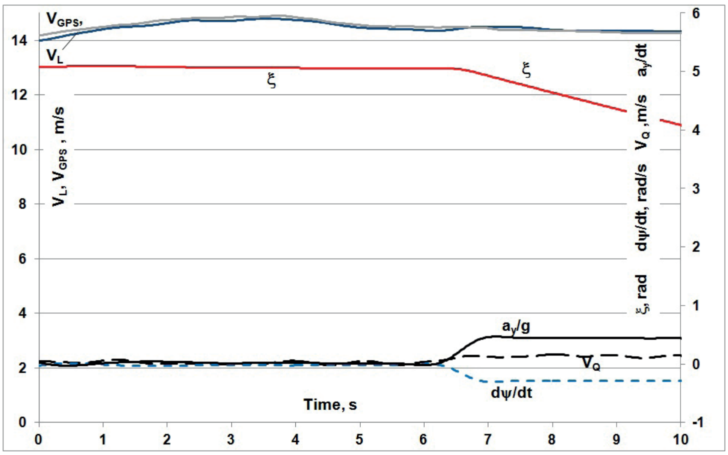

Fig. 5. Runs after preliminary processing (please compare with Fig. 4); velocity V_{GPS} measured in the GPS system and components V_L, V_Q of velocity measured in point C with the use of the Correvit sensor (please see Figure. 2); lateral acceleration a_y/g (as percent of gravitational acceleration) is also shown. The time scale of considered fragment start from 0 (see also Figure.4).

Data processing was realised in three parts:

a) Sideslip angle calculation according to formula (2) – this requires a heading angle ξ differentiation at first, summarising $(d\psi/dt)$ and $(d\xi/dt)$ next in purpose to sideslip angle rate ($d\beta_{GPS}/dt$) obtaining (sideslip angle which is calculated on the basis GPS data will be denominated as β_{GPS} in future). This β_{GPS} angle is a result of the integration of (2) in the defined time period according to formula (3).

b) Sideslip angle β_C calculation according to formula $\beta_C = \mathrm{atan}(V_{M,y}/\ V_{M,y})$, where $V_{M,x}$ and $V_{M,y}$ are velocity components of mass centre M – these components are calculated on the basis of V_Q and V_L measured with the aid of Correvit S-CE sensor. The components $V_{M,x}$ and $V_{M,y}$ are obtained after the reduction of V_Q and V_L to mass centre M from point C (see Figure. 2) according to the following formulas (see, for example,[12], [16]):

$$V_{M,x} = V_L - y_C\left(\frac{d\psi}{dt}\right) \qquad V_{M,y} = V_Q + x_C\left(\frac{d\psi}{dt}\right) \tag{4}$$

$$\beta_C = \tan^{-1}\frac{V_{M,y}}{V_{M,x}} \tag{5}$$

where: $d\psi/dt$ is the yaw rate measured with the aid of the IMU block; x_C, y_C are coordinates of the pavement piercing point of Correvit sensor's optical axle (see Figure. 2).

c) Error estimation and analysis

The resulting sideslip angles for steady state part of test (the part of runs between 7th and 10th s on the Figure 5) are presented in Figure. 6.

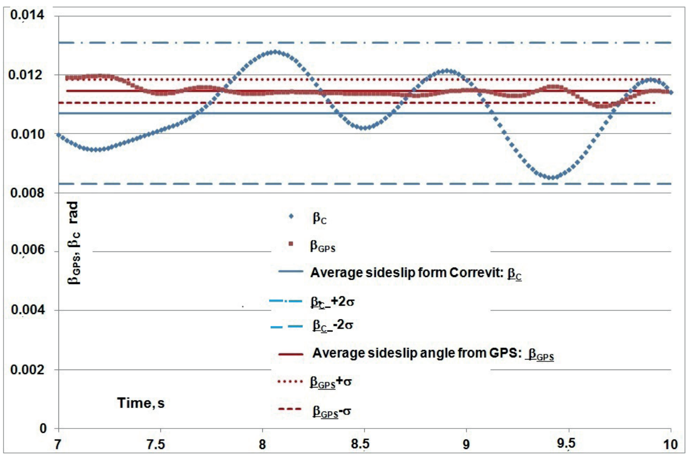

Fig. 6. The resulting sideslip angles (β_C, β_{GPS}) and their averages with standard deviations (σ) in the steady state part of test (the scale on time axis scale starts from steady state moment of test)

It follows from Figure 6 that the average values β_C ('sideslip from Correvit') and average value β_{GPS} (sideslip GPS in this) are not far from each other (see also Table 3). However, the calculated run of β_C is characterised by irregular undulation. This run occurs within the range of four standard deviations. The run of sideslip β_{GPS} occurs only within two standard deviations. This can be connected with various measuring sensitivities of the GPS engine (especially with regard to heading measurement) and Correvit sensor readings (especially with regard to measurement of V_Q lateral component of velocity – see runs V_Q on Figure 4).

As a second example of the application of the above-presented method, the results of sideslip calculation for a prototype 'bolid' style racing car are shown.

The main technical data for this vehicle is as follows:

Total mass (during tests) – 894 kg; wheel base – L = 2.650 m; mass distribution front/rear axle = 346/548 kg (rear engine and drive elements position); tire size (front and rear wheels) 215/45 R17; inflation pressure front/rear tires – 0.23/0.25 MPa.

The results presented below have been obtained on the basis of measurement data from GPS Vbox 3i type apparatus using.

A steady state test (realised by constant speed and variable steering angle method [4], [6]).

The results of sideslip angle estimation in graphical form is presented in Figure 7. The run of this angle is showed as function as lateral acceleration (according to ISO 4138 requirements). The run of steering wheel angle is also drew for general knowledge about steering characteristic of tested vehicle.

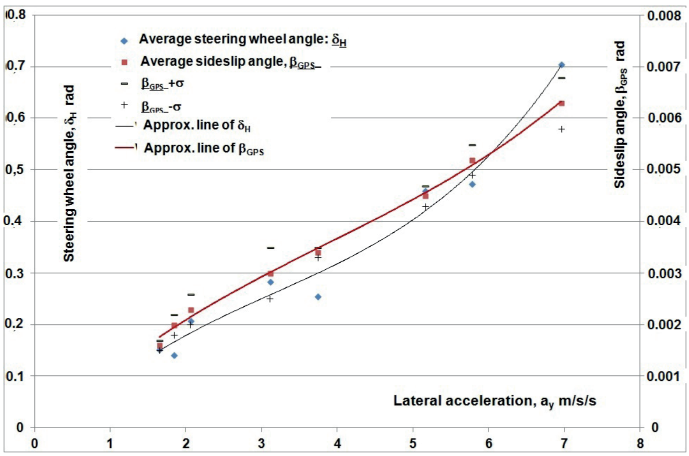

Fig. 7. Steady state circular test [6], [10]; constant speed test method; test velocity 80 km/h (22.22 m/s); left turn run; sideslip angle (β_{GPS}) calculated on the basis according to proposed method and steering wheel angle (δ_H) as function of lateral acceleration.

4. Error estimation and analysis

The error analysis was performed in detail for first example using statistical methods [7], [11], [15],[21].

Tab. 2. The main parameters of the statistical calculation of errors for first example

	Statistical parameters of errors	Before filtering	After filtering
Heading angle from GPS engine ξ, rad	A	4.5	4.5
	σ	0.002	0.25
Derivative heading angle $d\xi/dt$,rad/s	A	N.A.	0.28
	σ	N.A.	0.008
Yaw rate measured by IMU ($d\psi/dt$), rad/s	A	-0.2917	-0.2900
	σ	0.009	0.005
Longitudinal component of velocity from Correvit sensor placed at point C, V_L, m/s (see Fig. 2)	A	14.59	14.38
	σ	0.19	0.08
Lateral component of velocity from Correvit sensor placed at C point, V_Q, m/s	A	0.22	0.29
	σ	0.08	0.02
V_{Mx} of velocity measured by Correvit sensor at point C and reduced to point M, m/s (see Fig. 2)	A	N.A.	14.3
	σ	N.A.	0.1
V_{My} of velocity measured by Correvit sensor at point C and reduced to point M, m/s	A	N.A.	0.15
	σ	N.A.	0.02
Velocity from GPS engine, V_{GPS} m/s	A	14.32	N.A.
	σ	0.05	N.A.

A – average value (undertaken symbols in Fig. 6), σ – Standard deviation, N.A. – not applicable

The averages and standard deviations for runs of each of the measured parameters were calculated; this enabled calculation of the resulting sideslip angle error which took the form of a complex value. (see formulas in section 2). Of course, formulas for non-direct measured quantities and appropriate theory was applied (see, for example, [11]).

In Table 2, a selected parameters of errors calculation are presented.

Table 3 presents the main statistical factors of error calculation for resulting sideslip angles.

Tab. 3. The main statistical factors of error calculation for resulting sideslip angles

Sideslip angle from GPS system β_{GPS}, rad		Sideslip angle from Correvit system β_C, rad		$\frac{\beta_C - \beta_{GPS}}{\beta_C}$
A	σ	A	σ	
0.0114	±0.0004	0.107	±0.0012	0.078

A – average, σ – standard deviation

5. Concluding remarks

In the author's opinion, the sideslip angle (β_{GPS}) calculated with the application of measurement data obtained from a one-antenna GPS device could be used in practice.

From comparison with another calculation method (Correvit system) based on the non-contact measurement of longitudinal and lateral velocity components, it follows that the differences between average values of sideslip angles obtained from both considered methods is not greater than 8%. It can be observed that the run of sideslip (β_{GPS}) occurs within a bandwidth of only two standard deviations and has a smooth appearance. Sideslip (β_C) occurs within a bandwidth of four standard deviations. This can also be related to various measuring sensitivities (please see Chapter 4).

6. Acknowledgement

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