Article citation info:
PYTKA J, TARKOWSKI P, KUPICZ W. A research of vehicle stability on deformable surfaces. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2013; 15 (3): 290–295.

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A RESEARCH OF VEHICLE STABILITY ON DEFORMABLE SURFACES

BADANIE STABILNOŚCI RUCHU SAMOCHODU NA PODŁOŻACH ODKSZTAŁCALNYCH*

The paper includes results form a research of ride stability of a SUV (Sport Utility Vehicle), driven over deformable surfaces. An analytical method, in which stability of a mathematical model of vehicle's lateral dynamics is tested. The mathematical model has been reconstructed by means of a system identification method. We have used steering wheel angle as an input signal and lateral acceleration, side slip angle and yaw velocity as output signals to create the model. The data required to perform system identification have been gathered in a full size experiment, with the use of an instrumented vehicle. Final results in a form of poles and zeros diagrams have been included in the paper together with a discussion.

Keywords: *vehicle ride stability, lateral dynamics, offroad vehicles, deformable surfaces, system identification.*

W artykule zawarto wyniki badań stabilności ruchu samochodu osobowo-terenowego na podłożu odkształcalnym. Zastosowano analityczną metodę badania stabilności, w której badana jest stabilność matematycznego modelu danego obiektu. W rozpatrywanym przypadku, model matematyczny odtworzono na podstawie analizy sygnałów wejściowych (kąt obrotu kierownicy) oraz wyjściowych (przyspieszenie boczne i kąt bocznego znoszenia środka ciężkości, prędkość kątowa odchylania od kierunku ruchu, moment na kole kierownicy), z zastosowaniem metody identyfikacji systemów.

Słowa kluczowe: *stabilność ruchu, dynamika ruchu samochodu, podłoża odkształcalne, metoda identyfikacji systemów.*

1. Introduction

Vehicle stability can be tested by means of a variety of methods. One of them is that we assume stability analysis will be performed based on experimental data. Trajectory of the vehicle ride has to be determined and the stability can be performed by analyzing this trajectory and observing if the trajectory is within a stability margin. However, this method is of low accuracy and time consuming. Subjective valuation may lead to erroneous conclusions. One of the possible methods to evaluate ride stability of a vehicle is testing of its mathematical model. In this method, eigenvalues or roots of the so called characteristic equation of the model are evaluated. For a given system to be stable, or to have positive stability requires all the roots have negative real components.

A purpose of the present study was to apply the system identification and stability analysis method to evaluate ride stability of a SUV, driven over deformable surfaces.

2. Modeling of lateral dynamics of a SUV by system identification

System identification (SI) is a process in which a model and its parameters are reconstructed based on experimental data. There is a wide range of methods used for SI, from simple approximation to complex statistical analysis (Ljung, 1999). The method is widely used in modeling of aircraft dynamics and control (Klein and Morelli, 2006). Also, modeling studies in vehicle dynamics have been performed by means of the SI method (James, 2002). Reconstruction of mathematical models by means of the SI method may provide with sufficient data to perform stability analysis. It is needed, however, the experimental data used for identification procedures are fully informative for a given system. Based on the data models of linear and nonlinear systems can be reconstructed. When the identified model is linear, it is possible to analyze stability of a modeled system by means of eigenvalues evaluation. The procedure, called the zeros and poles test, gives an accurate verdict.

Instrumentation and measurements

Analysis if ride stability of a vehicle can be performed based on lateral dynamics analysis and therefore, the following measures are of high performance [1, 4, 5, 7]:

- lateral acceleration of the centre of gravity;
- yaw rate of the vehicle's gravity center;
- sideslip angle of the vehicle.

In our approach, the over-mentioned are output signals and the input will be steering wheel angle.

One of the requirements for the SI experiment is that the data obtained are accurate and informative. That can be fulfilled by designing the so called open-loop experiment. In other words, output signals have to be not dependent of the system response. It is not possible, when a person (driver) applies steering wheel angle as an input signal. One possible solution to apply here is to use a steering robot. We used ABDynamics steering robot, which consisted of five major subsystems:

- a motor unit mounted on the steering wheel
- a mounting fixture with torque transducers
- a control unit
- a power supply

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

– a computer with control software.

The steering robot can perform various steering scenarios to reproduce standard vehicle dynamic tests according to the ISO 7401, 3888, et cetera. One can also compose custom maneuvers by setting up important test parameters such as steering wheel angle rate 0 – 1800 deg/sec, frequency 0 – 10 Hz, steering wheel angle amplitude up to the limit of a vehicle, and duration of the maneuver. Installation of the robot in the research vehicle was simple with no special modifications (Figure 1). Before the test runs, the robot underwent typical procedures for aligning and setting the neutral point.

Measuring the input and output signals was performed with the following instrumentation:

- lateral acceleration, side slip angle and yaw rate have been measured by means of a DGPS (***D****igital* ***G****lobal* ***P****ositioning* ***S****ystem*);
- steering wheel moment and angle have been measured with the use of a instrumented steering wheel, which was one of the components of the steering robot.

The DGPS receiver coupled with an inertial platform has been used to measure kinematics parameter of vehicle motion. This system features 20-mm position accuracy at 10-ms acquisition time. It consists of an on-board subsystem (a receiver, power supply, and antenna) and a field-portable base station with external antenna. Coupling the DGPS with the robot allows to fully monitor vehicle motion and to define test runs by x-y coordinates of waypoints.

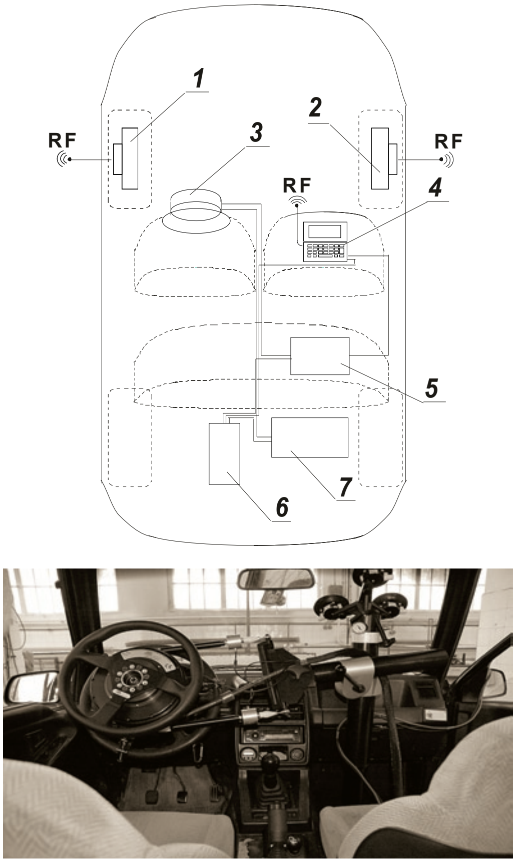

Fig. 1. A schematic of the instrumentation installed into the test vehicle and a cockpit view of the steering robot arrangement. 1, 2 – rotating wheel dynamometers, 3 – steering robot, 4 – interface computer, 5 – master computer, 6 – DGPS onboard unit, 7 – power supply

Procedures

The tests were performed on three different surfaces: sandy and loess soils and a wet snow surface. We chose loess and sandy soils as test surfaces because they represent different mechanical properties: cohesion for loess and internal friction for sand. The two soil materials are major components of many soil types. We conducted experiments on two different sites where the soil surfaces exist naturally: Sulejówek, near Warsaw, Central Poland for sandy soil and Paulinów, near Lublin, Southeast Poland for loess soil. The surfaces were rototilled after each pass of the test vehicle. Experiments on wet snow surface were carried out in February 2010 in Sulejówek. Snow depth was approximately 50cm, its density 500 – 700 kg/m^3, and temperature −0.3°C. We used only sine wave input for the snow surface experiments.

In the tests we have applied two different excitation methods: a step input excitation for dynamics test and a periodical excitation for steady state tests.

Ramp change (or trapezoidal) excitation mode is a typical dynamic method, in which we can determine dynamical response of the vehicle to continuously changing input. This ramp change input provides a substitute for step input (which is technically impossible to perform). Vehicle response has to be measured continuously and at a high sampling rate, since the observed parameters (yaw rate, lateral acceleration, sideslip angle, and the position of the center of gravity [CG]) changes dynamically, especially at the moment of and after the steering input.

Sine wave excitation is a typical steady state procedure. The vehicle is steered by harmonic excitation of the steering wheel at a given frequency and amplitude. We used 0.5, 1.0, and 2.5 Hz frequencies and ± 90 deg amplitudes. Vehicle response (yaw rate, lateral acceleration, and sideslip angle) is observed when it reaches stability (after a couple of steering periods). This requires that the test be performed on a sufficiently long test track.

Both excitation variants are presented in Figure 3.The three values of steering angle rate for ramp change excitation were 100, 500, and 1500 deg/s, while the amplitude was 180 degrees. The frequencies of sine wave excitation were 0.5, 1.0, and 2.5 Hz, with an amplitude of 90 degrees. The steering ratio of the vehicle used for the test was 1 to 9. A graphical presentation of the excitation modes is given in figure 2.

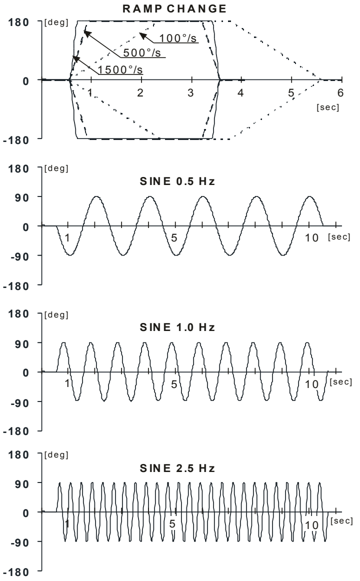

Fig. 2. Steering wheel excitation modes

The vehicle was driven in 4×4 mode (mechanically coupled drive chain, all four wheels driven) with a reduction gear on. The velocity of the test rides was approximately 10 km/h – almost the highest possible speed on those surfaces at low slip conditions. At least five replications were performed for each test variant.

3. The method of evaluation of the vehicle ride stability

One method of stability testing is the so called zeros and poles test. Stability of a given system is positive (the system is stable) if eigenvalues of the following equation:

$$\ddot{x}(t)+2\xi\omega_n\dot{x}(t)-\omega_n^2x(t)=bu(t) \tag{1}$$

are placed within the (−1;1) range. With roots, which have their real part is higher then 1 and imaginary part is zero, a system is unstable and we can say about non periodic instability. If an imaginary part is different from zero, the instability is of an oscillating type. Possible cases are shown in figure 3. If the roots have only real components (there aren't complex roots), we can speak of an asymptotical stability of the tested system (Figure 3a). If there are such roots (complex roots), the response of the system is of oscillating character (b). Those oscillations would disappear faster for roots placed apart of the imaginary axis. If one of the toots is placed exactly on the imaginary axis, the system has marginal stability and the oscillations will not disappear. For positive roots, right to the imaginary axis, the system is not stable (c and d).

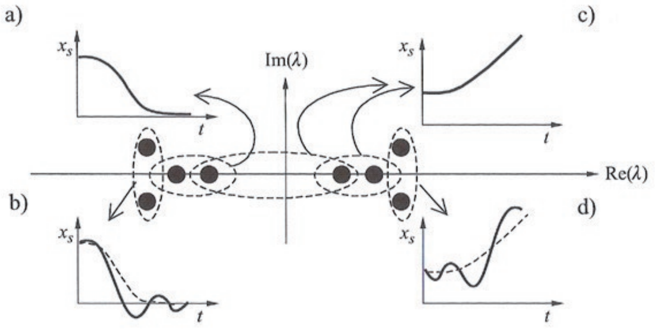

Fig. 3. Possible locations of eigenvalues of the characteristic equation of the model and their effects on stability (see text)

The software used to perform zeros and poles testing allowed to analyze the roots as well as poles, which are points where the model function has an asymptote.

4. Results and analysis

Figures 4 thru 18 contains results of performed zeros and poles tests for the models of lateral dynamics of the vehicle, based on experimental data obtained in the experiments performed on two different surfaces. Results for both periodical as well as ramp change steering input are included.

Based on the results presented in figs. 4 thru 6 we can say the stability evaluation based on lateral acceleration data is positive for loess and wet snow surfaces, at 1 Hz excitation. For the remaining variations we obtained negative evaluation of vehicle stability. The highest instability, quantified by means of real component value, was observed on sandy soil surface. This can be related to high deformability of this surface, what leads to deep ruts and consequently tripping the roadwheels of the vehicle. This may be the cause of the so called *tripped roll-over*, a very frequent scenario of accidents in cases of leaving the road [8].

The three following figures, 7 – 9 show the results for the second important lateral dynamics measure, the side slip angle.

Evaluation of vehicle stability based on side slip angle data shows a diverse trend. Here, positive stability occurs on sandy soil surface only. There are some but not numerous exceptions, moreover these roots are very close to stability margins. Physically, it can be explained as follows: the wheels grip the surface as the ruts are deep and no significant yaw motion is possible. A quite different trend was observed on loess soil surface. The wheels don't sink deep into the soil so they do a lot of side slipping and consequently yawing motion of the vehicle is much more visible. A similar situation occurred on wet snow. That was rather unexpected, since deep ruts in snow could eventually help to keep the track, but a high decrease in wheel-surface friction on wet snow played a more important role.

Figures 10 thru 12 show root locus plots for the third measure that is important for lateral dynamics of a vehicle, the yaw rate.

Analyzing these graphs, we have concluded the motion of the test vehicle to be least stable. For the yaw rate, there has been observed the highest value of real part of a root. It was 20,38, noticed on sandy loess surface. Moreover, instability occurred on all the three surfaces, loess, sandy and wet snow. On loess surface a case of periodical instability was observed. The only stable motion occurred on sandy soil surface for 1,0 Hz sine wave excitation.

Another step in our study was an analysis of vehicle motion for trapezoidal steering excitation. The method of stability analyzing was similar to that for sine wave excitation. Autoregressive models have been reconstructed from measured data of steering angle as an input parameter and for the three lateral dynamics measures, as output signals. Figures 13 thr 18 contains root locus plots for the two soil surfaces (no data for wet snow surface has been collected). Stability evaluation based on lateral acceleration is shown in figs 13 and 14.

The figures consist of two graphs, one of them represents turning to the left, another to the right. We observed instability for the two surfaces, generally for higher values of steering wheel angular velocity (500 and 1500 deg/s). In case of sandy soil surface, instability occurred at the lowest velocity (100 deg/s), while for the remaining higher velocities vehicle motion was stable. On the loess surface there was observed the highest instability (Re = 18,22 for 500 deg/s) while on the sandy soil surface a periodic instability was observed at 500 deg/s.

Stability evaluation of the vehicle motion based side slip angle data and yaw rate was similar to that obtained with sine wave excitation tests. Figures 15 and 16 show results for the evaluation based on side slip angle data. There was noticed instability for test runs on loess soil surface for all the three steering wheel angular velocities. Moreover, a periodic instability occurred at 100 deg/s. Results for the two directions of turning (to the right and to the left) are similar. On sandy soil surface, vehicle motion was stable only for the lowest steering wheel angular velocity. For the remaining cases, at 500 and 1500 deg/s there was noticed instability. At 1500 deg/s by turning to the left and at 500 deg/s and turning to the right there were observed severe oscillations.

The third important measure used for evaluation of vehicle motion stability by trapezoidal excitation of the steering wheel was yaw rate. Root locus plots obtained based on yaw rate analysis is shown in figures 17 i 18. By turning to the right on loess soil surface, vehicle motion was stable at 100 deg/s, for the remaining excitations we observed instability. By turning to the left, the highest instability was noticed at 500 deg/s (Re = 17,76). For both, turning to the right and to the left, oscillating instability occurred at 500 deg/s. Zeros and poles tests based on data gathered during test rides over sandy soil surfaces showed instability for all cases of angular velocity of the steering wheel. On the other side, there was no oscillating instability in those tests.

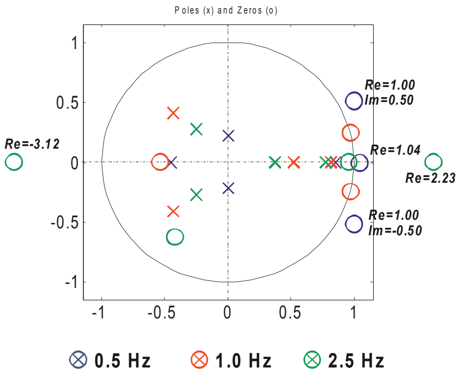

Fig. 4. Root locus plot for sine wave excitation, lateral acceleration. Tests on less soil surface

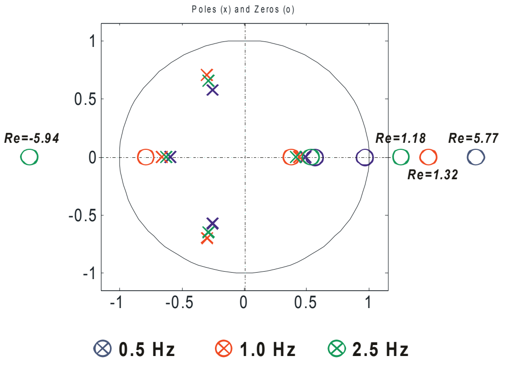

Fig. 5. Root locus plot for sine wave excitation, lateral acceleration. Tests on sandy soil surface

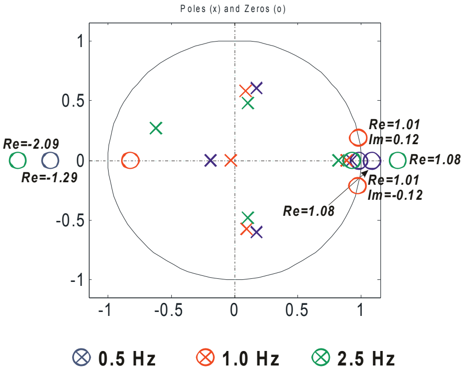

Fig. 6. Root locus plot for sine wave excitation, lateral acceleration. Tests on wet snow surface

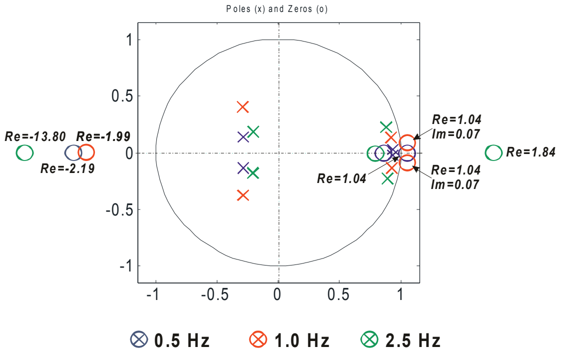

Fig. 7. Root locus plot for sine wave excitation, side slip angle. Tests on less soil surface

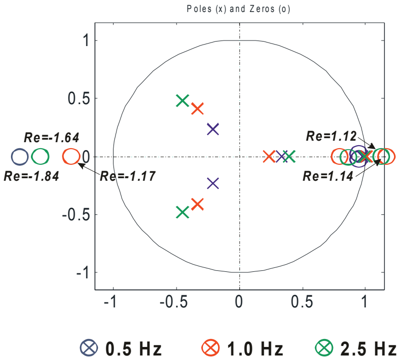

Fig. 8. Root locus plot for sine wave excitation, side slip angle. Tests on sandy soil surface

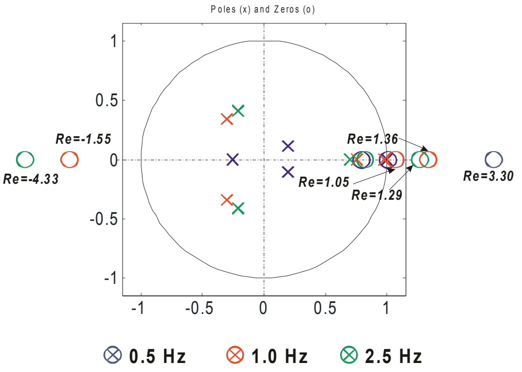

Fig. 9. Root locus plot for sine wave excitation, side slip angle. Tests on wet snow surface

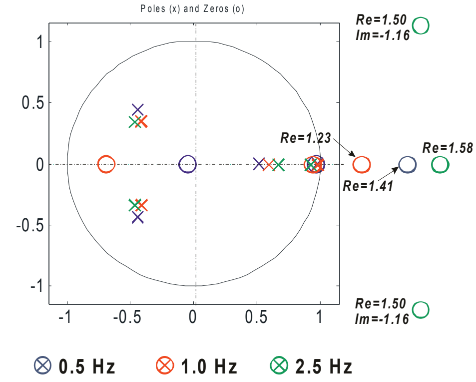

Fig. 10. Root locus plot for sine wave excitation, yaw rate. Tests on less soil surface

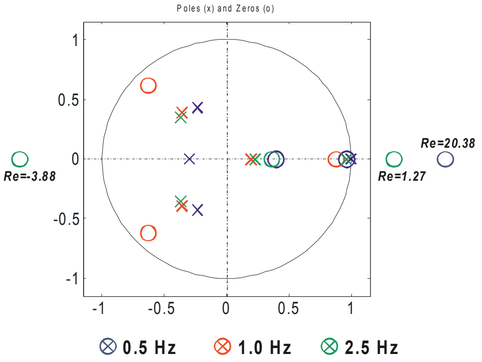

Fig. 11. Root locus plot for sine wave excitation, yaw rate. Tests on sandy soil surface

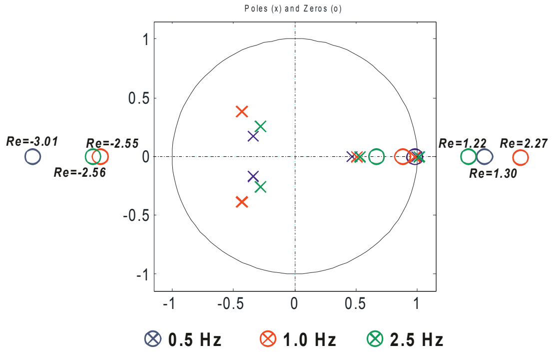

Fig. 12. Root locus plot for sine wave excitation, yaw rate. Tests on wet snow surface

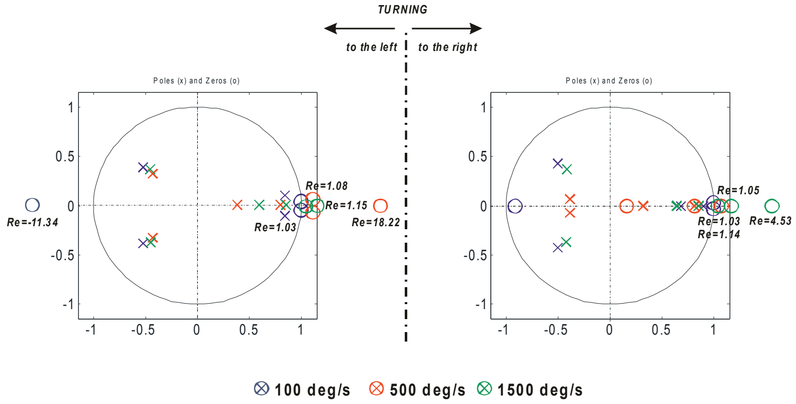

Fig. 13. Root locus plot for trapezoidal excitation, lateral acceleration. Tests on less soil surface

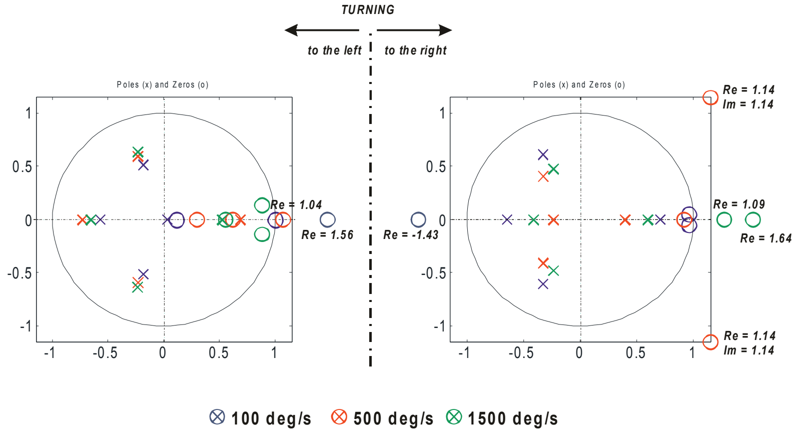

Fig. 14. Root locus plot for trapezoidal excitation, lateral acceleration. Tests on sandy soil surface

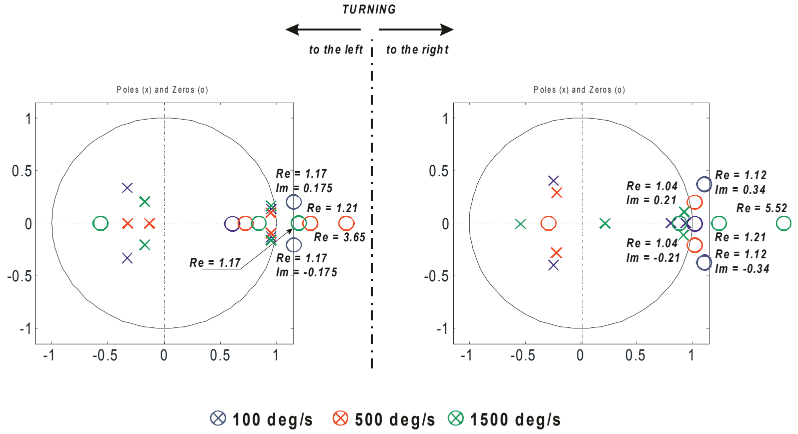

Fig. 15. Root locus plot for trapezoidal excitation, side slip angle. Tests on less soil surface

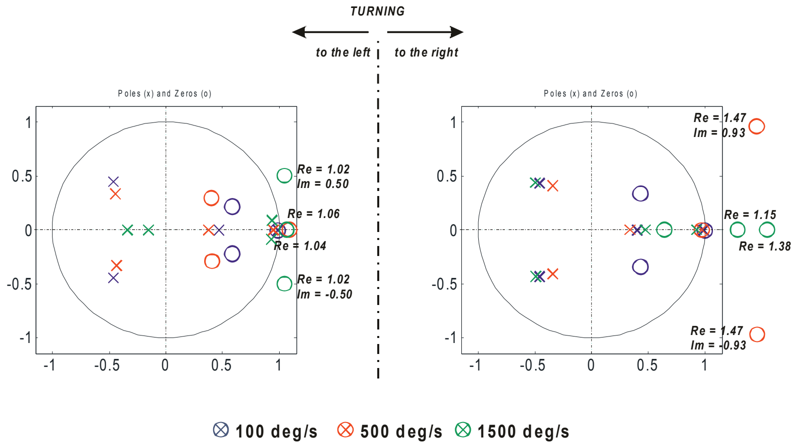

Fig. 16. Root locus plot for trapezoidal excitation, side slip angle. Tests on sandy soil surface

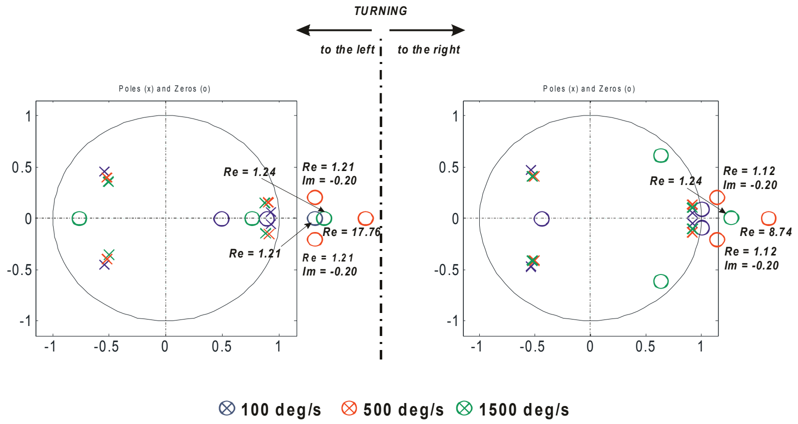

Fig. 17. Root locus plot for trapezoidal excitation, yaw rate. Tests on less soil surface

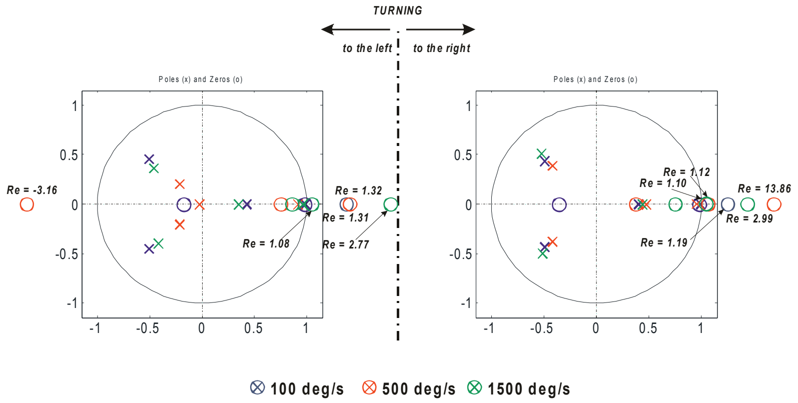

Fig. 18. Root locus plot for trapezoidal excitation, yaw rate. Tests on sandy soil surface

Acknowledgments:

This study has been financially supported from the Polish Ministry of Science and Higher Education as a research project (grant) no. 5389/B/T02/2011/40, in the years 2011 - 2013

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