Lateral dynamics of a SUV on deformable surfaces by system identification. Part I. Identification experiment

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Abstract. The paper presents a study on lateral dynamics of a 1.6 tonne Sport Utility Vehicle (SUV) on deformable surfaces performed by means of system identification method. The first part of this study describes an identification experiment, methods and procedures. The identification experiment, in which steering wheel rotation was an input and vehicle motion in the lateral direction was an output has been conducted on three different surfaces: a loess and a sandy soil and on wet snow. The vehicle used for the experiment was equipped with a steering robot to apply repeatable excitations and a high precision Digital Global Positioning System (DGPS) system to gather dynamic response of the test vehicle, physical measures of the resulting motion: lateral acceleration, yaw rate and vehicle side slip angle. The vehicle was driven with a constant speed of 10km/h. The steering robot input sine wave excitation at 0.5, 1.0 and 2.5 Hz, as well as ramp change (or trapezoidal) excitation with steering wheel rate of 100, 500 and 1500deg/s. It was concluded the methods applied in the field tests were informative and in the sense of the system identification method.

1. Introduction

Lateral dynamics of a vehicle, either in a turn or straight drive with random disturbances plays a significant role in ride safety and comfort [1]. Numerous accidents and incidents that occur off-road are strong motivation to aim this problem. Also, research towards deeper understanding of phenomena [2 - 5], especially dynamic response of a vehicle to steering inputs can be valuable for designers of vehicle undercarriage and steering systems, especially the controllers of traction assistance systems.

One of reasons for difficulties in modelling and simulation of wheel – soil or vehicle – terrain interactions is the complexity of most deformable surfaces [6 – 14]. A typical soil is a three phase medium with a very unstable particle composition, resulting in high deviation of physical and mechanical parameters. Soil sensitivity on moisture content adds to variability of soil surface mechanical state.

The aim of this study was to apply a diverse method to the problem of vehicle dynamics on deformable surfaces – the system identification method. In this method, autoregressive models are reconstructed from input and output data measured on a subject object [15 – 17]. The paper presents an identification experiment, especially methodology developed for field tests that have been performed with the use of a Sport utility Vehicle (SUV) running over soil and snow surfaces. It has been proposed the use of a steering robot to perform the experiment in the closed – loop mode. This device ensures high repeatability of excitation inputs and a wide range of dynamic parameters (steer
angle rate, frequency, steering torque). Dynamic response of the test vehicle was sensed by means of a high accuracy differential GPS system coupled with an inertial navigation.

2. Experimental methods

2.1. Test vehicle and instrumentation

The philosophy of the author was to use a real object – a vehicle running on chosen deformable surfaces. The following sections describe the test vehicle, instrumentation and procedures. Excitation modes performed by means of the steering robot are also presented as important elements of the identification experiment.

2.1.1. The vehicle

In the present study an instrumented vehicle with a steering robot has been used to perform both ramp change and sine wave input methods. The vehicle was 1995 Suzuki Grand Vitara, powered by a 1.6 dcm³ spark ignition engine of 104 HP. The vehicle has a maximum weight of 1650 kg, the actual weight for the tests was 1400 kg and 195/R15 75 off-road treaded tyres. On the vehicle two systems were installed: a steering robot and a DGPS coupled with an inertial navigation. Additionally, four rotating wheel dynamometers have been installed on the vehicle to measure side force on road wheels. The instrumented vehicle running over the loess soil surface is shown in figure 1, for more details please refer to the reference by Pytka et al [14]. Description of the instruments included in the test vehicle follows.

![Figure 1](image.png)

**Figure 1.** The Suzuki Vitara instrumented vehicle during the field tests on loess soil surface
Figure 2. A schematic of the instrumentation installed in the test vehicle. 1, 2 – rotating wheel dynamometers, 3 – steering wheel robot, 4 – control and data acquisition computer, 5 – DGPS/IMU computer, 6 – DGPS sensor, 7 – power supply

2.1.2. Steering robot

The steering robot system consists of the following elements: motor unit mounted on the steering wheel, mounting fixture with two transducers (measuring steer torque), central control unit, power supply and a computer with control software. The motor unit is a direct drive and can be mounted simply on the steering wheel of a vehicle or on a steering column through an adaptor. The mounting fixture serves as a reaction frame for the motor generating high torque and is mounted between the windshield and floor of the vehicle. The system is capable of reproducing standard vehicle dynamics tests according to ISO standards as well as to realize custom designed tests at the following parameter ranges:

- steer angle rate up to 1800 deg/s
- frequency up to 10 Hz.

The robot system installed in the test vehicle is shown in figure 3.

Figure 3. Installation of the steering robot in the test vehicle: mounting fixture with the sensing elements in the front right of the vehicle and the motor unit mounted on the steering wheel of the vehicle.
2.1.3. The DGPS navigation system

Vehicle lateral motion, physically a response to the excitations by the robot during steady forward ride is described by a set of measures: displacement, velocity and acceleration along the three orthogonal axes. These measures were captured with the use of an integrated navigation system of high accuracy. The system is based on a differential global positioning system receiver and an inertial measurement unit (IMU). The GPS/IMU sensor is the on-board part of the system, while a differential base station was placed out-board the vehicle and the two subsystems were connected with a RF interface. Such system enables to maximize accuracy of vehicle position determination by referencing approximation. Before use the complete system has to be initialized by connecting within the subsystems and with the satellites. One portable computer was used to control and synchronize both the steering robot and the GPS/IMU system. Figure 4 shows the sensor together with the power supply installed in the test vehicle.

![Figure 4](image_url)

**Figure 4.** The motion sensing instrument (DGPS+IMU, a small red box) was installed in the rear compartment of the test vehicle. This required to input relative coordinates of the unit placement in order to transform the measured data to the centre of gravity of the test vehicle. The bigger silver box is the main power supply for the steering robot system.

2.1.4. Rotating wheel dynamometers

Rotating wheel dynamometers (RWD) installed on the instrumented vehicle were designed by the author and are to measure six elements: three orthogonal forces and three moments acting on a road wheel of the test vehicle. The complete RWD system consists of: (1) the sensor, built with the use of a strain gage transducer, (2) the modified wheel rim, (3) the mounting system, and (4) the data recording system. A schematic of the mechanical components is shown in figure 5. The RWD system is capable of simultaneous measurements of three forces: $F_v$, $F_x$, and $F_y$, as well as three moments: $M_v$, $M_x$, and $M_y$ acting on a wheel. The measurements can be performed with a test vehicle in either on-road or off-road conditions. The test vehicle requires no modification to its structure; the only part to be modified is a wheel rim.

The heart of the RWD is the sensor. The device was designed to fit into modified wheel rims of diameters between 14 and 16 in. (35.6 and 40.6 cm). The design allowed for a central hub extension of 100 mm diameter because, in many four-wheel driven (4WD) vehicles, front drive is attached by an additional mechanical clutch located in the hub extension. The sensor core was made of steel, and strain gages were used as sensing elements. The sensor is a modular, all-in-one measuring device with outgoing signals ready for analog to digital (A-D) conversion and recording.

The sensor was calibrated on a test stand with a legalized precision dynamometer for obtaining the $V$-$kN$ and $V$-$Nm$ factors. The calibration test stand was adapted from a conventional fatigue tester. Calibration tests were carried out for every single-force channel, and the sensor was positioned in the
test rig accordingly for the particular test. The results show very good linearity of the sensor (less than 2% on each element).

The data recording system has two parts: a transceiver attached to the dynamometer and a receiver in a portable computer located in the vehicle. The transceiver module consists of an A-D converter of 16-bit resolution and eight single-ended channels with sampling rate of 100 per second for each of eight channels. The data is converted to digital form and then transmitted by radio frequency to the receiver. The transmission is based on the 2.4GHz Bluetooth standard and is performed simultaneously for every active channels of all four RWDs.

![Figure 5. A schematic of the rotating wheel dynamometer (top) and the dynamometer installed on the test vehicle (bottom).](image)

2.2. Procedures and manoeuvres

In testing of dynamics of any object it is very important to choose the right excitation method, since the general approach assumes analysis of vehicle’s response to exciting inputs. Typical tests for lateral dynamics are step input and sine wave input methods [18, 19]. A steering wheel of a test vehicle is being excited by means of either step or sine wave input and this excitation is usually done by a test driver [20]. Since a true step input is not possible in real conditions, a so called ramp change or trapezoidal input is used in vehicle testing. A steering wheel is set for a given angle at a constant rate, after reaching the given angle, the wheel is held in the position for about 3 – 6 seconds, then it is set back at a previously used angle rate to neutral position. According to ISO 7401, the angle rate should be as high as possible, more than 200 deg/s. In sine wave input test, the steering wheel is set continuously at a sinusoidal change of angle with a given amplitude and frequency for a period of time that allows to obtain steady state conditions. The following paragraph describes the experimental setup and procedures.
The tests were performed on three different surfaces: sandy soil, loess soil and wet snow. Choosing loess and sandy soils as test surfaces was reasonable, since they represent different mechanical properties: cohesion, which is typical for loess and internal friction for sands. The two soil materials are major components of many soil types.

Experiments were conducted on two different sites, where the soil surfaces exist naturally: Sulejówek, near Warsaw, Central Poland for sandy soil and Paulinów, near Lublin, South-East Poland for loess soil. The surfaces were preconditioned during the tests by rototilling after each pass of the test vehicle. Experiments on wet snow surface were carried out in February 2010 in Sulejówek. Snow depth was approx. 0.3m, its density 500 – 700kg/m$^3$ and temperature -0.3°C. On snow surface only rides with sine wave excitation were performed.

For ramp change excitation, three values of angle rate were chosen: 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, amplitude 90 degrees. A graphical presentation of the excitation modes is given in figure 6.

The vehicle was driven at 4x4 mode (mechanically coupled drive chain, all four wheels driven) with a reduction gear on. The velocity of the test rides was approx. 10 km/h and it was almost the highest possible speed on those surfaces at low wheels slip. At least five replications were performed for each test variant.

![Figure 6. Two modes of steering wheel excitation: ramp change (or trapezoidal) at 500 deg/s and sine wave excitation at 1 Hz frequency.](image)

3. Results

Figures 7 thru 10 shows typical results of field measurements, obtained at ramp change and sine wave excitations respectively. In the graphs, time courses of the vehicle dynamics measures have been presented together with steer angle course (thick line) shown for reference. Dynamics effects, such as time delay or over-steering are clearly visible in the graphs. The character of the curves is very similar for all measurements variants/repetitions.
Figure 7. Sample data obtained in field experiments: time courses of the four vehicle dynamics measures for the sine wave excitation mode at 1.0 Hz frequency. Results for the sandy soil surface
Figure 8. Sample data obtained in field experiments: time courses of the four vehicle dynamics measures for the ramp change excitation mode at 500deg/s steering rate. Results for the loess soil surface.
4. Conclusions

Experimental research on vehicle lateral dynamics for a 1.6 tonne SUV running over two soils, loess and sand and over wet snow has been performed. In this research, vehicle lateral acceleration, yaw rate, side slip angle and steering wheel torque have been determined for two excitation modes: sine wave and trapezoidal.

It has been concluded that the methods applied in this study ensured to design and perform the informative identification experiment and provided with results which can be used as input and output data for the identification procedures. Reconstruction of autoregressive models of vehicle lateral dynamics with the use of these results is described in the second part of this study.

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