

Steering Effects Upon Lateral Dynamics of a SUV On Deformable Surfaces

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Lublin University of Technology

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ABSTRACT

We studied the effect of steering dynamics on lateral dynamics for a 1.6 tonne 4×4 sport utility vehicle (SUV) on deformable surfaces. The vehicle used for the outdoor tests was equipped with (1) a steering robot to apply repeatable steering wheel excitations and (2) a high-precision differential GPS (DGPS) system to gather physical measures that describe lateral dynamics: lateral acceleration, yaw rate, and vehicle sideslip angle. The vehicle was driven over three different deformable surfaces—a loess and a sandy soil and wet snow—with a constant speed of 10 km/h. The steering robot applied inputs of (1) sine wave excitation at 0.5, 1.0, and 2.5 Hz, and (2) ramp change (or trapezoidal) excitation with steering wheel rate at 100, 500, and 1500 deg/s. Results are presented as frequency paths and time courses to analyze effects of surface and steering dynamics. Data from ramp change input excitation tests were used to derive factors describing lateral vehicle dynamics: yaw rate gain, peak response time, and TB factor. We concluded that the test method was sensitive enough to analyze effects of surface and steering dynamics upon vehicle lateral dynamics. Prospective use of the results could be identification of lateral dynamics models or verification of existing models and algorithms.

INTRODUCTION

Deformability of a surface on which a vehicle is running affects ride performance significantly. Firstly, a deflection of the surface under the wheels results in higher rolling drag [6]. The energy consumed for volumetric deformation of the surface material can be correlated with the loss of energy in the rolling wheel. A fundamental mathematical representation of generating a rut depth and additional rolling drag is Bekker's model with three soil constants attributed to its

deformability, cohesion, and internal friction [2]. Another problem with surface deformability is a loss of traction, caused mainly by dilatational deformation in surface material. Longitudinal wheel forces (driving force and drawbar pull) are generated more by internal friction among the soil particles than by tread - surface dry friction, common for on-road applications. A basic mechanical model for developing of driving action on deformable surfaces came from Coulomb (1776) who derived a formula for shearing stress and taking into account an angle of internal friction and the cohesion. Much research has been devoted to the problem of off-road locomotion during past five decades, but some aspects still seem to be unsolved.

One of the difficulties in modeling and simulation of wheel-soil or vehicle-terrain interactions is the complexity of most deformable surfaces. 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 to moisture content adds to variability of the soil surface mechanical state. Typical soil surfaces mostly deform plastically. A typical sand has high internal friction and less cohesion, while loess soil has low internal friction and high cohesion, especially in wet conditions. When a soil is exposed to agricultural work (ploughing, etc.), its structure is very loose and deformability high. Loose soils can be successfully described using rheology models [5], but the most accurate results can be obtained by applying micromechanical or probabilistic models [11]. Soil surfaces with roots (plants growing on it) become a more stable structure with quasi-elastic characteristics. Such a surface can be found on grassy airfields. Perhaps the most deformable surface for vehicles is fresh snow at freezing temperatures. The density of fresh snow is about 0.05 - 0.1 g/cm³; it increases to as much as 0.7 g/cm³ after wheel traffic. A

material of such high deformability needs specific models, such as the crushable foam model used by Shoop (2001) [12].

This study examines lateral vehicle dynamics on deformable surfaces by experimental research. As most terramechanics research has focused on vehicle mobility and longitudinal rather than lateral dynamics. However, studies on lateral vehicle dynamics on deformable, soft surfaces may give important results for off-road transportation safety or for prevention of rollovers during road departure.

A number of studies have been done on lateral dynamics and vehicle stability in on-road conditions [1, 3, 7, 8, 9, 10, 13, 14], but those for off-road are relative rare. Deppermann, 1988 studied lateral vehicle dynamics on snow-covered roads to examine the effects of snow chains on vehicle performance. A technique of sine wave excitation of the steering wheel was used to detect vehicle dynamic response. Mitschke, Wallentowitz, 2005 pointed out this technique is most suitable in lateral dynamics studies for off-road conditions, since other techniques-the procedures suggested by the ISO 7401 standard [6]-are problematic because of difficulties with test repeatability and obtaining statistically representative results. To overcome those problems, we proposed the use of a steering robot to perform true sine wave and ramp change excitations of high repeatability. We sensed vehicle dynamic response with a high accuracy differential GPS (DGPS) system coupled with an inertial navigation platform.

EXPERIMENTAL SETUP AND PROCEDURES

Typical tests for lateral dynamics analysis are step input and sine wave input. Since a true step input is not possible in real conditions, a ramp change or trapezoidal input is used in vehicle testing. A steering wheel is set for a given angle at a constant rate: after that angle is reached, the wheel is held in the position for about 3-6 seconds, then it is set back to neutral at the previously used angle rate. According to ISO 7401 [6], the angle rate should be as high as possible, more than 200 deg/s. In a 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 long enough to reach a steady state. The vehicle's response is usually described by three measures: lateral acceleration, yaw rate, and sideslip angle.

THE INSTRUMENTED VEHICLE

This experimental study of lateral vehicle dynamics used an instrumented vehicle with a steering robot to realize both ramp change and sine wave input methods. The vehicle was a 1995 Suzuki Grand Vitara, powered by a 1.6dcm³ spark ignition engine of 104 HP power. The vehicle has 195/R15 75 off-road treaded tires and a maximum weight of 1650kg;

the actual weight for the tests was 1400kg. We installed two systems on the vehicle: a steering robot and a DGPS coupled with an inertial navigation.

The Steering Robot

The steering robot system consists of five elements:

- a motor unit mounted on the steering wheel ([figure 1 top](#))
- a mounting fixture with two transducers (measuring steer torque) ([figure 1 bottom](#))
- a central control unit
- a power supply
- a computer with control software



Figure 1. Installation of the steering robot in the test vehicle: a motor unit (top), a mounting fixture with torque transducers (bottom).

The motor unit is a direct drive and can be mounted 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 performing custom designed tests at the following parameter ranges:

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

The Motion Sensing System

We used an integrated navigation system of high accuracy to sense vehicle dynamic response. The system consists of a differential GPS receiver, a base station, and an inertial navigation platform. The GPS and the inertial platform are coupled in one package (figure 2) and are the on-board instrumentation. The base station with a low band antenna is outside the vehicle. This subsystem supports the GPS receiver to maximize accuracy of 20mm. Before use the complete system has to be initialized by connecting all the subsystems and the satellites. One portable computer controls both the steering robot and the navigation system. The software can set up the test scenarios and initialize tests as well as acquire data acquisition and perform primary analysis.



Figure 2. The receiver unit of the DGPS system

A summary of technical data of the instrumentation integrated into the research vehicle is shown on [table 1](#).

Table 1. Technical data of the devices integrated into the research vehicle

Equipment	Function	Range	Remarks
Steering robot	Steering wheel adjustment and movements	Angle rate: 0 – 1800 deg/s Frequency: 0 – 10 Hz	Commercially available
Wheel dynamometers	Measurements of: wheel forces, Fz, Fx, Fy; moments, Mz, Mx, My	Vertical load: 0 – 30 kN Horizontal forces: 0 – 10 kN Moments: 0 – 30 Nm	Custom design A set of four items installed on the vehicle
DGPS	Measurements of kinematical data: linear and angular speeds; accelerations, etc. Determining of vehicle position	Acquisition time: 10 ms Position: +/- 20 mm	Custom available An external reference station for better positioning
Correxit L400	Measurement of vehicle longitudinal velocity	Range: 0 – 250 km/h Preciseness: 0.01 km/h	Custom available A special version for offroad application
SST	Measurements of soil or snow pressures under wheel loads	Heavy SST: 0 – 700 kPa Mid SST: 0 – 500 kPa Light SST: 0 – 200 kPa	Custom design A set of three SSTs – for different loads – was used
TDR	Measurements of soil moisture content, soil salinity and electrical permittivity of snow	Soil moisture 0 – 100% at 0.1% Salinity at 0.1% El. permittivity at 0.01	Commercially available Portable, battery operated

FIELD PROCEDURES

The tests were performed on three different surfaces: sandy soil, loess soil, and wet snow. [Table 1](#) shows a selection of surface data. 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/m³, and temperature –0.3°C. We used only sine wave input for the snow surface experiments.

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 3](#).