METHOD FOR TESTING STEERABILITY AND STABILITY OF MILITARY VEHICLES MOTION USING SR60E STEERING ROBOT

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Abstract

The paper presents testing results that serve the development of research methodology for steerability and stability of military special-purpose vehicles using the SR 60th control robot. Due to their high centre of mass and a large moment of inertia of their body, armoured vehicles pose a serious hazard during dynamic maneuvers. The phenomenon of oversteering is dangerous, which causes automatic reduction in turning radius and thus increases the lateral acceleration at the high-lying centre of mass usually leads to the vehicle rollover. In conditions of a limited tractive adhesion, any slight side impulse (side wind, a drive through a road rut) is enough to result in the vehicle sideslip. At high inertia, each response of any surprised driver is delayed. Therefore, the research studies on behaviour of special-purpose vehicles, including the military ones during road tests are particularly dangerous. The developed methodology allows mitigating the risk of using the steering robot and enables to obtain a very high research results repeatability, unattainable even for a very skilled test driver. The procedure developed hereto is used to accurately determine the safe driving velocity while making sudden maneuvers, and for vehicles steerability characteristics. It may become an excellent tool to verify simulation models.

Keywords: *vehicles, steerability, testing methods, military, vehicles*

1. Introduction

Military vehicles for their purpose must have very good driving properties, steerability and motion stability. In combat conditions, a driver operates under high stress that contributes to mistakes made while driving a vehicle. In addition, the problem exacerbated in MRAP-type vehicles whose capsule – passenger compartment – is mines explosion-resistant and it is located at high altitude; and the centre of mass of the vehicle is located high, which significantly reduces the lateral stability. Before they are put into military service, vehicles are subject to extensive testing, inter alia, with respect to steerability and motion dynamic stability. In order for the testing process itself to be safe, a procedure has been developed that aims to mitigate the vehicle rollover risk during road tests. Thanks to the use of SR 60 steering robot, made by AB Dynamics for testing purposes, a very high repeatability of road tests results has been achieved. This will allow for a precise determination of safe operating conditions of the vehicles tested.

2. Description of Testing Apparatus

Military Institute of Armoured and Automotive Technology has a unique device to examine vehicle behaviour in road traffic conditions. This is the SR 60 steering robot made by AB Dynamics. The device consists of a few modules:

- central unit of high computing capacity;
- lag-satellite measurement system RT 3002;

- the user's computer for data recording and visualization.

View of the robot is illustrated in Fig. 1.

Fig. 1. Steering Robot. a. lag-satellite system RT 3002, b. central unit, c. measurement steering wheel with adjusting pillar

Maximum extortion torque on the steering wheel is 70 Nm. The maximum turn velocity is 2500°/s, angular resolution at 0.00076°, and angular accuracy of 0.2°, depending on load and velocity.

The so configured system allows:

- to program any driving path or use the ready standardized tests templates,
- to record and reconstruct the vehicle motion path while being operated by a driver,
- to measure responses of the system to extortion: measured are the following: longitudinal velocities, lateral and vertical, displacement and angular accelerations of the vehicle, lateral accelerations, and the vehicle steerability characteristics is determined,
- for conducting a test always at the same place, which is especially important if only a small yard is available to make measurements or the yard with heterogeneous surface,
- repeatability of vehicle motion trajectory with an accuracy of ±5 cm.

The research studies are performed by using two types of tests:

- open tests: at a precisely defined extortion of the turn angle and the angular velocity. The RT system is used in this case for recording the responses of the system to the precisely defined extortion,
- tests programmed by the motion path. The RT system positions the vehicle and the extortion depends on the vehicle behavior.

3. Testing

The testing was performed according to the following schedule:

1. Selection of a research object,
2. Determination of static parameters of:
   - distribution of mass onto the wheel axles and sides for two states of the load,
   - location of the center of mass for two states of the load,

- static angle of lateral yaw on the tangent plate with simultaneous measurement of the vehicle body roll angle against the plate,
- the vehicle body roll angle as a function of lateral force in static conditions,

3. Performance of tests at the airport for two states of the load:
    - execution of the „random noise” test at various driving velocities,
    - stability tests in a circular motion with a constant radius of 30 m and gradually increasing driving velocity [4],
    - test of sinusoidal extortion on the steering wheel test at various driving velocities [5],
    - "roll stability" – the rollover resistance test,
    - double traffic lane change [3].

4. Testing Results

A military all-terrain vehicle with a low-positioned centre of mass was selected for testing. The vehicle ensured the safe performance of maneuvers [1].

In the first stage, measurements of static parameters were made. The position of the centre of mass was determined as well as the lateral yaw static angle and the vehicle body yaw angle while trying to influence the lateral force applied at the centre of mass, under the static conditions.

Fig. 2 illustrates the measurement of the centre of mass and lateral yaw static angle.

Fig. 2. Determination of the Centre-of-Mass Position and the Lateral Roll Static Angle

Results of the performed static tests allow concluding that:

- the load of 225 kg placed on the floor by the back door led to a backward shift in the centre of mass by 146 mm and down by 31 mm,
- the tested vehicle has a "rigid suspension" that effects in small vehicle body yaw angles,
- there is full correlation between the body yaw angle as specified during the test on the tangent plate and during the impact of the lateral force. The vehicle body roll angle determined under static conditions can serve as a boundary parameter beyond which there is danger of the vehicle rollover during maneuvers in road tests.

Then tests were performed on the tarmac using the SR 60 steering robot. the repeatability of tests, some attempts of sinusoidal extortion was performed on the steering wheel with a frequency of 0.5 Hz and 1 Hz. A standard deviation of the average extortion (of the steering wheel turn angle) value and a response (lateral acceleration and yaw angular velocity) were assumed as a measure of the results dispersion. The analyses results were presented in Tab. 1.

Tab. 1. Dispersion of Results while the Sinusoidal Extortion Test

Parameter	Turn to the			
	Left		right	
	Frequency of Extortion Hz			
	0.5	1	0,5	1
1	2	3	4	5
Maximum angular velocity of the steering wheel turn [°/s]	291	568	302	631
Maximum torque on the steering wheel [Nm]	12.5	31.74	13.1	34.12
Average turn angle of the steering wheel [°]	90.01	89.89	89.97	89.98
Standard yaw of the steering wheel turn angle	0.01	0.02	0.01	0.02
The average amplitude of lateral acceleration [m/s/s]	5.17	4.45	5.89	4.92
The standard deviation of the lateral acceleration	0.14	0.08	0.12	0.1
Average amplitude of the yaw angular velocity [°/s]	13.07	21.94	15.6	23.27
The standard deviation of the yaw velocity	0.57	0.98	0.65	0.48

Driving in a Fixed Radius Circle at Gradually Increasing Driving Velocity

The tests were performed conducted while driving in a circle with a radius of 30 m, and with gradually increasing velocity until the lateral slip prevented the vehicle from staying on its desired motion path.

The recorded signals of lateral acceleration yaw velocity, and the steering wheel torque went through the Butterworth filter of order 11 with cut-off frequency of 5 Hz. [4, 5]

The steerability gradient was calculated and by defined formula (1).

$$GS = \frac{1}{i_s}\frac{d\delta_H}{da_y} - \frac{d\delta_A}{da_y}, \tag{1}$$

where:

δ_A - the wheels turn theoretical angle resulting from the Ackermann’s formula, required for a vehicle, having a wheelbase of l [3], to move along an arc with a radius R:

$$\delta_A = \frac{l}{R}.$$

The testing results indicated that the backward shift in the centre of mass ("loaded" variant) causes as follows:

- the reduced wheels turn angle, required for driving on a circle of given radius,
- the reduced steering wheel torque (SR Torq),
- the vehicle’s reduced lateral wandering angle,
- the reduced steerability gradient.

The testing results for both variants of the load were illustrated in Fig. 3- 6.

Tests of the Vehicle Behaviour During Sinusoidal Extortion

The tests were performed for the two states of the load – for a vehicle with its curb weight and loaded with a mass of 225 kg placed by the back door. The driving velocity was matched so that the lateral acceleration amplitude would reach ca. 4 m/s^2. Exemplary time processes for the frequency of 1 Hz were illustrated in Fig. 7 - 9.

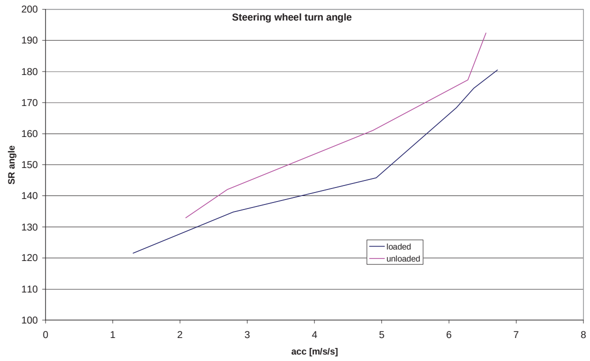

Fig. 3. Steering wheel turn angle, required for driving on a radius of 30 m in the lateral acceleration function

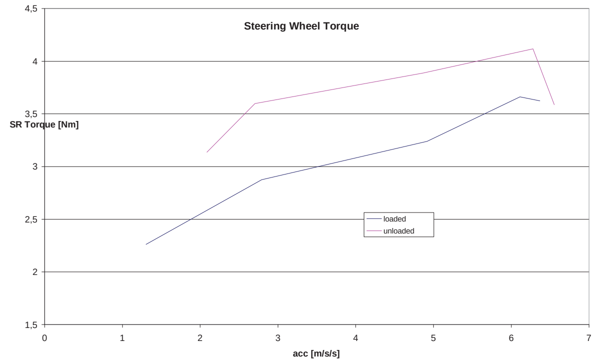

Fig. 4. Steering Wheel Torque (SR Torq) in Lateral Acceleration Function

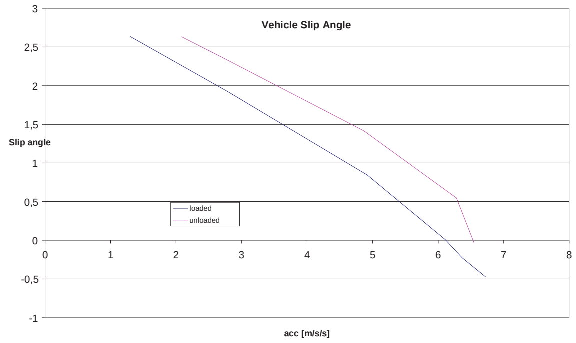

Fig. 5. Vehicle Slip Angle in Lateral Acceleration Function

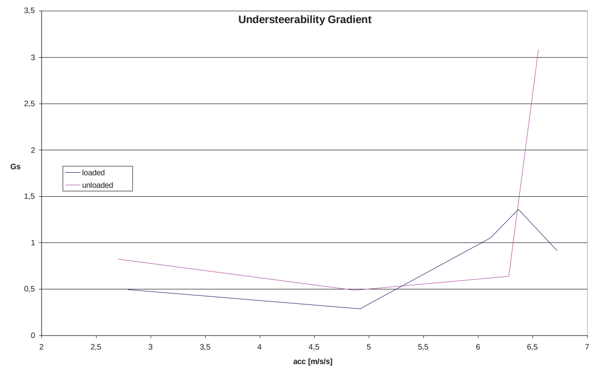

Fig. 6. Steerability Gradient in Lateral Acceleration Function

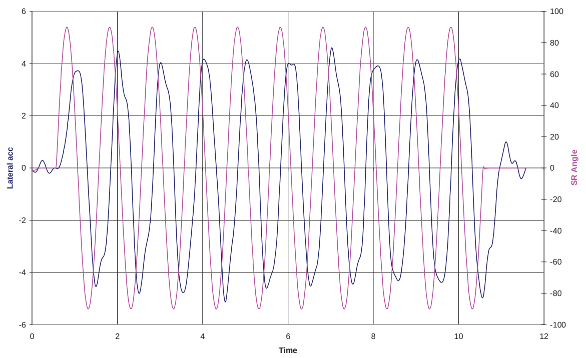

Fig. 7. Time Processes of Steering Wheel Turn Angle and Lateral Acceleration

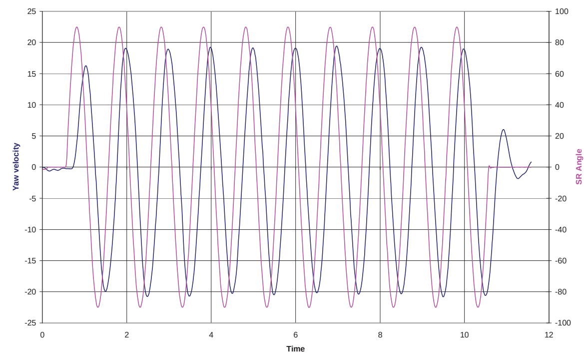

Fig. 8. Time Processes of the Steering Wheel Turn Angle and the Angular Yaw Velocity

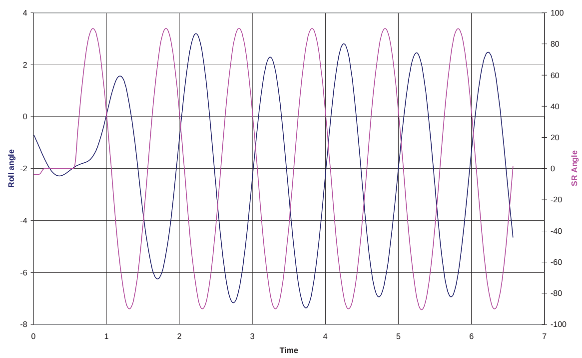

Fig. 9. Time Processes of the Steering Wheel Turn Angle and the Body Roll Angle

Phase transitions were determined between the extortion and the response of the system for two frequencies: 0.5 Hz and 1 Hz, and the amplification coefficients for lateral acceleration and angular yaw velocity from the formula (2) and (3):

$$yaw_{gain} = \frac{|yaw_{\max}|}{|SRangle_{\max}|}, \tag{2}$$

$$ac_{gain} = \frac{|ac_{\max}|}{|SRangle_{\max}|}, \tag{3}$$

The results were presented in Fig. 10 - 11.

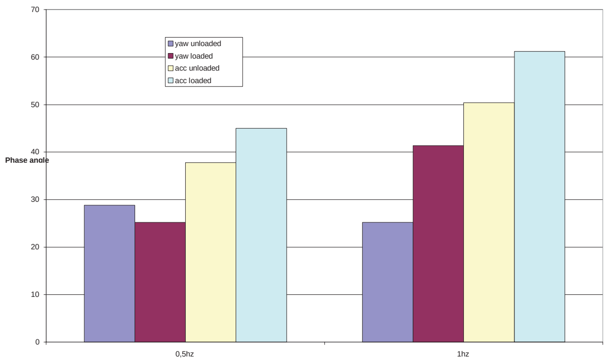

Fig. 10. Phase transition angle between extortion and response of the system

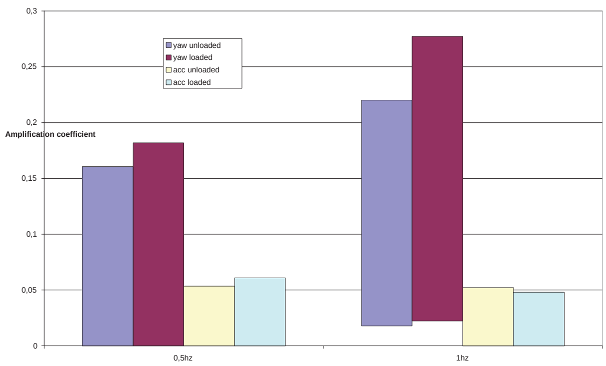

Fig. 11. Amplification coefficients of the lateral acceleration and the angular yaw velocity

Lateral Stability Test – Roll Stability

The resistance of the vehicle to rollover is determined during this test. Upon reaching a steady state due to the angular velocity of the vehicle body, the initial extortion with the steering wheel into one direction changes into the extortion towards the opposite direction at high angular yaw velocity of the steering wheel. The vehicle body is affected by centrifugal force applied at the centre of mass and additionally the response force of the suspension springs and stabilizers. A safe velocity is determined at which there is no excessive body roll angle.

Fig. 12 presents the processes of the lateral roll angle for various driving velocities.

The analysis of time processes of the body roll angle indicates that the driving velocity affects the value of the roll angle only to a certain point. This is due to the increasing lateral slip angle that results in a reduced lateral acceleration.

Testing of Vehicle Behaviour During Double-Lane-Change Manoeuvre

The double-lane-change test should be carried out at the end. It simulates the actual road situation such as pedestrian incursion onto the road. Tests should be started from low velocities and upon every test run the time process of the vehicle roll angle should be controlled. The trajectory should be designated by cones and in addition the progress of *the Path following error* should be analyzed. Within the maximum possible velocities, the speed should be increased with a gradually lower step - 2 or 1 km/h.

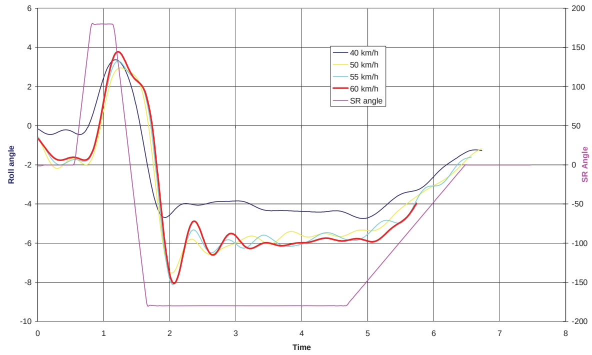

Fig. 12. Time processes of the lateral roll angle during the stability test

There is also a need for keeping a very accurate driving velocity during the entire test. It is desirable that the velocity should vary no more than 1 km/h. The maximum safe velocity is the one at which it was possible to perform the manoeuvre three times without precipitation of the cones / excessive path following error, and a dangerous lateral roll angle. Tests should be carried out in both traffic directions.

Sample processes are illustrated in Fig. 13.

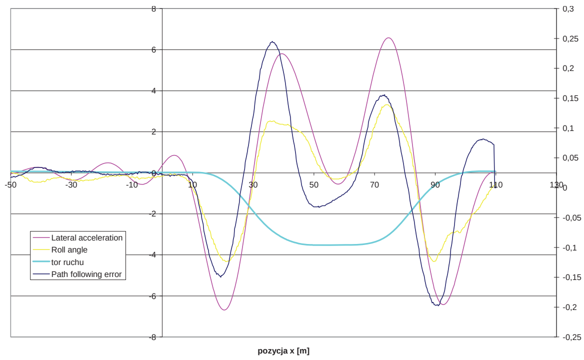

Fig. 13. Time processes of parameters measured during the double-lane-change manoeuvre

5. Summary

The basic problem in vehicle steerability research studies is the impact of a driving style of the driver on the repeatability of test results. Detailed analyses of the testing results that are obtained by using traditional method proved to have significant dispersions in the performance of test maneuvers by the same driver, and in particular, those differences were evident when comparing three different drivers. A use of the steering robot in the developed test procedures has eliminated the problem of no reproducible results. This allows for a more objective and accurate assessment of the vehicle in its road tests. The results of the tests performed indicate that:

- before each test on the tarmac, some measurements should be taken in the vehicle, namely: the mass distribution on the wheel axles and the sides, the position of the centre of mass and the theoretical lateral roll angle should be determined, and a boundary roll angle on the plate while simultaneously measuring the body roll angle. This is very important for safety reasons,
- body roll angle that has been determined on the tangent plate is identical with roll angle determined while testing how the lateral force affects the vehicle and the body roll angle gained during road tests. It may, therefore, indicate that carrying out the maneuvers at higher roll angles is associated with a high risk of the vehicle rollover,

- a dispersion of results has been determined both of the extortion and the response of the system while tests using the SR 60 robot. The results obtained indicate a very high repeatability of results,
- special precautions should be taken during road tests of special-purpose vehicles and each series of measurements should be initiated at the lowest velocities.

The procedure developed hereto is used to accurately determine the safe driving velocity while making sudden maneuvers, and for vehicles steerability characteristics. It may become an excellent tool to verify simulation models.

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