MODELLING AND VALIDATION OF A TESTING TRAILER FOR ABS AND TYRE INTERACTION ON ROUGH TERRAIN

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Abstract

The main purpose of a vehicle anti-lock braking system (ABS) is to prevent the tyres from locking-up in order to brake efficiently whilst maintaining steering control and stability. Sport utility vehicles (SUV) are designed to drive on various roads under different driving conditions, making it challenging to identify optimal operating conditions for ABS algorithms to be implemented.

This paper describes the development and modelling of a testing trailer that is designed to benefit the research of a SUV tyre operating in ABS braking modes on non-deformable rough terrain. The test trailer can be to investigate the variation of tyre contact forces and vibration characteristics influenced by ABS braking and rough terrain excitation. Undesirable fluctuations of wheel speed, normal force and braking moments make measurements more complicated and limits the performance of active safety systems. A trailer made from a Land Rover Defender chassis is used with standard ABS components and is implemented with a Bosch ABS algorithm for experimental tests. In addition to the ABS system the necessary measuring equipment such as Wheel Force Transducers (WFT), accelerometers, brake pressure transducers, GPS and vehicle speed measurement instrumentation is used.

An Adams model of the trailer in co-simulation with ABS and test control in MATLAB/Simulink is created to validate the model. The centre of gravity position and inertia characteristics of the trailer are determined through experimental testing. A validated FTire tyre model, suitable for off-road conditions, is incorporated to accurately resemble the specific tyre used during tests. The validated Adams model and test trailer will enable further development of ABS algorithms including the identification of key parameters through which ABS braking can be optimised for various roads as well as optimizing interaction with semi-active suspension systems.

Keywords: anti-lock braking system, ABS, tyre vibration, rough terrain, ADAMS, FTire

1. Introduction

Nowadays safe vehicle driving is supplemented by various active safety systems. Generally all these systems rely on making interaction between tyre and road pavement as effective as possible which improves the handling and braking characteristics of the vehicle. As the Sport Utility Vehicle (SUV) has become increasingly popular, improving anti-lock braking system (ABS) performance on rough terrain is important.

In this paper the review of ABS problematics on rough terrain is detailed. The development, modelling, and model validation of the test rig used to research SUV tyres operating in ABS braking mode on non-deformable rough roads is presented in order to analyse the variation of contact forces and vibration characteristics.

2. Review of deterioration of ABS on rough terrain

Available literature highlights the problems with ABS braking on rough terrain, these problems occur mainly in three areas namely: 1) the algorithm used, 2) the vibration response of the tyres and 3) sensing parameters required as inputs to the algorithms.

One of the oldest and best documented ABS algorithm is described by Bauer and Bosch (1999). This type of ABS control loop has 8 phases that are initiated by various thresholds based on the angular acceleration/deceleration of the wheels. For each phase a braking state is set where the brake pressure is controlled. There are three braking states: *Pump*, *Dump* or *Hold*. This algorithm is the default ABS control strategy through which ABS braking tests will be conducted.

The variations of wheel rotation caused by rough road and ABS braking was analysed by numerical calculations of Marian et al. (2009). Large fluctuations in tyre vertical load, angular wheel speed and acceleration pose problems of misinformation for the control logic of ABS.

The deterioration of ABS performance on rough terrain was analysed through using of test vehicle and a simulation model by Penny and Els (2016). The main factors causing the deterioration of ABS was the accurate measurement of vehicle velocity during experimental tests and the existing response delays within the braking system during modelling. It was further found that the angular acceleration of the wheels on smooth road and pressure with braking distance on Belgian Paving showed poor correlation between test and simulation data.

Researchers of ABS for electric powered vehicles also confirm the relevance of this topic (Ivanov et al., 2015). Desensitization factor is introduced in continuous wheel slip control function and simulations for low-friction and off-road driving conditions were performed as the most important for ABS design.

The comparison between the vibration response of a rolling tyre with road impact excitations and a non-rolling tyre showed that a road impact mainly excites the tyre in the frequency band below 300 Hz (Kindt et al., 2009). The significant drop of tyre resonance frequencies at around 50 Hz and 100 Hz was determined at rolling speeds of 17 km/h and 28.3 km/h respectively. The valuable conclusion of that research for tyre rolling on rough road is that the excitation amplitude dependency is restricted to the tyre's sidewall stiffness.

After rolling tyre vibration measurements Tsujiuchi et al. (2004) determined that the vibration velocity level of the tyre's leading edge is higher than the trailing edge. The dominant peaks of vibration velocity level of rolling tyre are between 70 Hz and 150 Hz, but the range of forced excitation received from a road surface is very narrow.

Experimental measurements and modelling based on cylindrical shell theory done by Koizumi et al. (2010), found that tyre rotation has no effect on the first vibration mode. Further modes in range of 50–300 Hz have been influenced by loading and rotation conditions. Pauwelussen et al. (2003), in research of SWIFT rigid ring tyre model application to ABS braking performance, detected tyre resonances near 30 Hz and 75 Hz which match the tyre's in-plane and out-of-plane rotational modes. The first eigen frequency is sensitive to brake torque and vertical wheel load, but mostly to velocity. An additional eigen frequency of 120 Hz was determined through analysing the tyre's stiffness and inertia influence on tyre dynamics. Although larger brake force variations (less damped tyre) was captured at lower velocities, numerical calculation of full vehicle dynamics does not clearly show tyre behaviour.

The properties of a tyre's sidewall are specific for SUV tyres and have different influences on its vibration characteristics. The increase of apex length and carcass width induces the decrease of vibration energy, but the increase of sidewall gauge and apex hardness induces the increase of vibration energy (Lee and Kim, 2008).

SUV type tyres tend to have larger variation of torsional stiffness and damping which has a negative influence on interaction with standard ABS controllers. Adcox et al. (2012) performed research on tyre torsional dynamics and ABS controller filter cut-off frequency sensitivity to vehicle stopping distance. After sensitivity analysis it was found that cut-off frequencies lower than 15 Hz removed most of the tyre-wheel dynamics and causes the decrease in vehicle stopping distance.

An experimental study of the influence of tyre design parameters such as carcass stiffness, tread compound and tread stiffness influence on ABS braking performance was done by Sivaramakrishnan et al. (2015). Peak grip, braking stiffness, optimal slip ratio and shape factor were distinguished as the main tyre characteristics. The braking stiffness was expressed as a combination of carcass stiffness and tread stiffness and the latter is the dominant factor during the initial braking cycles in the pressure build up stage. Since the first cycle of braking can cause the most loss in the stopping distance, braking stiffness was determined as a significant parameter in ABS performance. The tread compound also causes a large influence on the efficiency of the ABS algorithm which could also be related to vehicle suspension setup.

Road roughness (Zuraulis et al. 2014), as well as the variation of friction between tyre and ground, are essential factors in analysis of ABS braking and design of new control algorithms. Botero et al. (2007) has implemented ABS logic based on wheels forces and moments real time sensing for rough road conditions. Numerical simulations showed a 10% reduction of vehicle stopping distance by reducing brake pressure jumps and normalised longitudinal force variations in subsequent braking cycles.

In transient tyre behaviour, the slip applied at the axle differs from the slip based on the rotation of the tyre. During ABS braking, decreasing the speed of the vehicle decreases the damping ratio of the wheel and thus increases the oscillations in the rotational speed (Pauwelussen, 2015). The author also highlights the increase of lag between the actual longitudinal slip at the tyre-road contact and the slip at the axle during repetitive braking. For this reason the tyre slip-ratio for contact force analysis should be captured by measuring tyre tread speed and ground speed at the contact patch (Botha and Els, 2015). Determination of the tyre slip-ratio directly from video images using digital image correlation techniques avoids the uncertainties caused by measuring inaccuracies of vehicle speed and tyre roll radius or road roughness. Otherwise radial deformations of the tyre in frequency up to 300 Hz could also be used for analysis of tyre forces (Xiong and Tuononen, 2015). As radial and tangential deformations are symmetric regarding the contact patch during vertical wheel load, braking force causes the increase of deformation shape asymmetry. The radius of braked tyre is smaller before the contact with the road so measurement of tyre slip-ratio from speed of the vehicle and the wheel is complicated and optical sensors a suitable solution.

The main non-linearities of the slip characteristics and contact patch relaxation length, as well as the vertical load dependency of the dynamic tyre radius, were determined using rigid ring tyre model in case of brake torque variations study by Zegelaar (1998). Although a rigid ring tyre model is suitable for vibration analysis up to 80 Hz, appreciable uncertainties appear from frequencies of 50 Hz. In Zegelaar’s, work the frequency response function from measurement data of longitudinal force to brake variations clearly indicates modes of 35, 80, 90 and near 100 Hz. From the frequency response function of slip variation data a first resonance frequency of 65 Hz is determined. The increase of relative tyre damping at higher velocity and lower vertical load was also identified during a stepwise increasing brake pressure test which excited a tyre in-plane rotational mode at 33 Hz.

Jaiswal et al. (2009) analysed three single-point tyre models for ABS braking performance. After mathematical simulations, it was found that tyre’s oscillatory behaviour is related to its relaxation length, which should be expressed in relation with tyre vertical load, slip and contact patch mass damping. Braking simulations is in a straight-line, while cornering and with a step pressure variation showed an increase of longitudinal slip and contact force oscillations as the speed of the vehicle reduces. Sensitivities of tyre relaxation length and response lag for ABS braking performance lead to further analysis in for avoiding wheel speed and ABS controller disturbances.

3. Experimental setup

Terrain or off-road driving is driving on unprepared ground, where the tire is in contact with natural surfaces or dirt roads, while driving on prepared ground is where the tire is in contact with paved or concrete surfaces (Genta and Morello, 2009). Moreover, driving on rough terrain induces specific vehicle and tyre dynamic characteristics (Pazooki et al., 2012, Bosch et al., 2016).

To isolate the effect of tyre-ABS interactions, a specially equipped trailer was prepared for measurement of ABS braked tyre performance. To avoid any suspension influence and to analyse only tyre performance, the axle was rigidly fixed to the trailer frame. Only straight line steering (zero angle) for trailer‘s wheels was allowed.

A Wabco hydraulic modulator without an ECU controller was incorporated into the braking system of the test trailer.

A Hardware-in-the-loop (HIL) system from dSPACE (MicroAutoBox) was used for data logging, real-time brake actuation and ABS control. The wheel speeds were measured through using a Variable Reluctance Amplifier and a DSPIC. The LM1815 (Variable reluctance) chip was used to convert the raw ABS speed sensor outputs into pulse signals which were used as inputs for the DSPIC chip's interrupt pin that converts the frequency of the signal to an output voltage. The voltage is read using the MicroAutoBox which converts the voltage to wheel angular speed.

Wheel force transducers (WFT), trailer's tow hitch force transducer, brake pressure transducers, accelerometers, laser displacement sensors and accurate GPS sensor systems from Racelogic was mounted on the test trailer for logging dynamic parameters necessary for model validation. For test repeatability the trailer's braking system was activated using a pedal actuator.

Two drums were filled with cement to make up 1 ton of ballast to simulate the appropriate weight that the tyres experience on a SUV vehicle. The fully loaded and equipped test trailer is shown in Fig. 1.

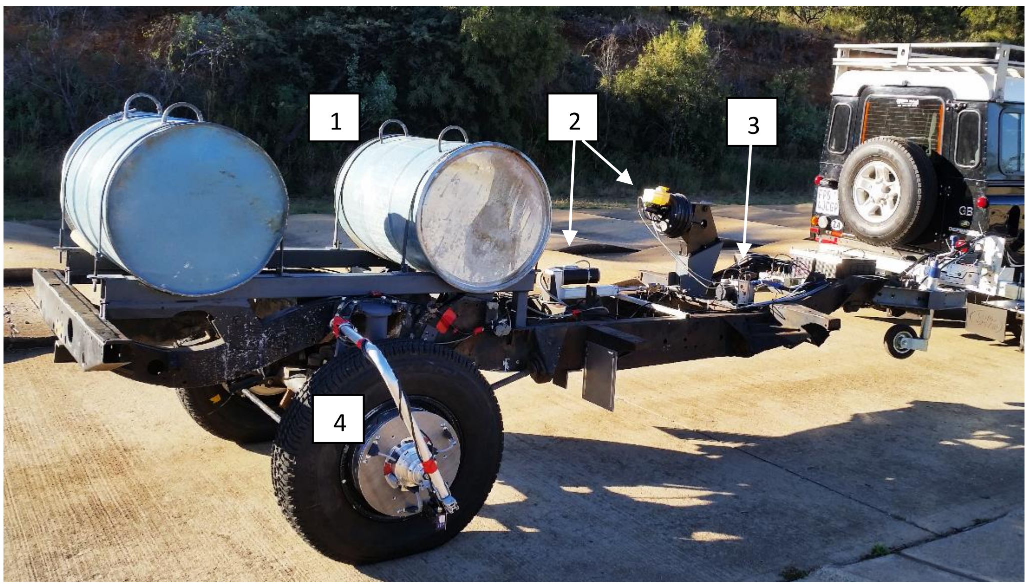


Fig. 1. *Test trailer fully loaded and equipped:*
1 – optional loads, 2 – brake pedal with actuator, 3 – ABS modulator, 4 – wheel force transducer (WFT)

4. ADAMS model validation

A model of the test trailer was created in MSC ADAMS/View. The center of gravity (CG) and moments of inertia of the test trailer was obtained by measuring the period of oscillation about a pivoting axis (Uys et al., 2006) was determined (Table 1 and Fig. 2). The values were used to specify the main parts of the test trailer (frame and axis) in the ADAMS model. CG and inertias of additional parts such as weights for vertical load, batteries and wheels with WFT were measured and calculated separately and added into model.

Table 1. Moments of inertia and center of gravity of test trailer

Trailer load conditions	Mass, kg	Moments of inertia, kg·m^2 (without wheels and WFT)			Centre of gravity, m		
		I_{roll}	I_{pitch}	I_{yaw}	Longitudinal distance from the wheel axle	Lateral distance from the symmetry axis	Vertical distance from the ground
Chassis	570	66.36	887.20	3204.45	0.823	0.01	0.615
with load I	1027	295.21	996.65	4701.88	0.644	0.063	0.894
with load II	1547	476.95	1610.02	12851.40	0.223	0.042	0.986

Fig. 2. *Determination of center of gravity and Inertia for test trailer*

A FTire model of the Michelin LTX A/T[2] 235/85R16 SUV, used on the trailer was implemented in the ADAMS model. This tyre model was selected because of its accurate application for rough terrain conditions (Bosch et al., 2016). Parameterization data for footprint, hardness, vertical stiffness on different cleats, lateral, longitudinal and torsional stiffness and modal analysis was used to construct FTire model.

The trailer model (Fig. 3.) is controlled by implementing co-simulation between MATLAB/Simulink and Adams software. Longitudinal, lateral and vertical positions on trailer's tow hitch and brake torques for each wheel were assigned as model input values sent from Simulink. As pulling forces are used directly from measured data, brake torques are recalculated from measured pressures. Moreover, the same Bosch ABS algorithm used during experiments was to be used for brake pressure control in ADAMS simulations.

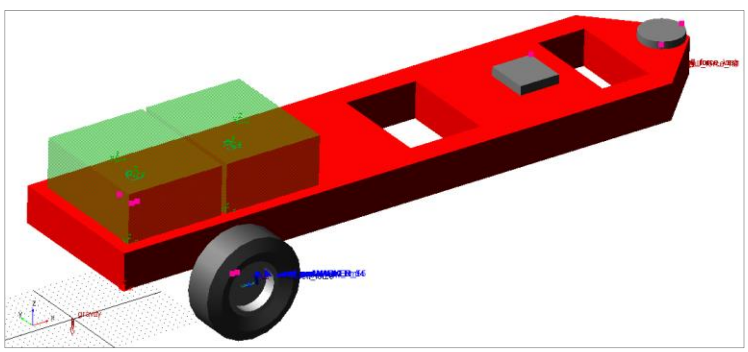


Fig. 3. *ADAMS model of tyre test trailer with added optional loads*

Since the tyre's forces and its variation are necessary for further analysis, the longitudinal and vertical forces acting on wheel hub were identified as the most important characteristics for model validation. Wheel speed (velocity) is also compared as it a significant input for the ABS algorithm.

Model validation tests were conducted using two 100 mm high ramps to investigate tyre force response by comparing test data with simulation data. The preliminary tests were done with no load on the trailer. The trailer was towed by a vehicle using an extender beam connected to the towing point to create an offset, so that only the trailer travels over the ramps. The validation tests involving the ramps were done through driving the trailer over both ramps placed synchronously at speeds of 10km/h and 20km/h (Fig. 4.). At 10 km/h the tyres remained in contact with the road but, due to the fact that the trailer has no suspension, it becomes airborne at 20 km/h as indicated in Fig. 4b.

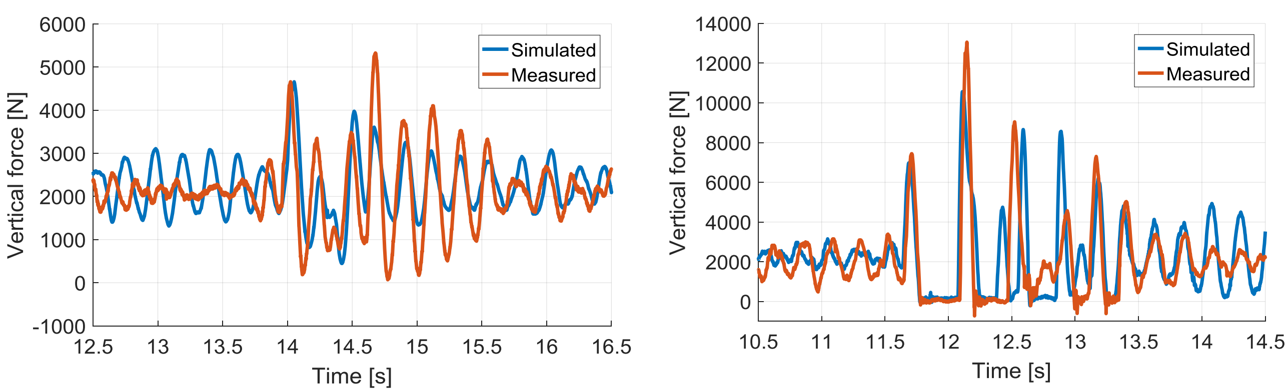
a) b)

Fig. 4. *ADAMS model validation over two symmetric ramps: a) 10 km/h b) 20 km/h*

The model validation tests at 10 km/h and 20 km/h (Fig. 5.) shows that the same natural frequency is excited in the two measurements – this shows that the inertias for the trailer has been measured correctly. The measured tyre response of dynamic vertical force correlates relatively well with the simulated tyre response. The magnitude of the peaks for the measure data after the initial peak after 14.4 seconds in Fig. 5a are greater than the simulated data possibly because of added dynamics from the towing vehicle.

The ramps are 1.7 m long, thus traveling at 20 km/h, it takes 0.3 seconds to drive over the ramp. With regards to the model validation test at 20 km/h (Fig. 5b), it is observed that the first peak around the force of 7 kN occurs when the trailer enters the ramp. The measured and simulated data from the first peak up to the second (interval between 11.2 and 12.2 sec) shows good correlation. It is within this timeframe that the trailer drives over the ramp, thus validation in terms of the trailer's interaction with the ramps is good in Fig. 5b.

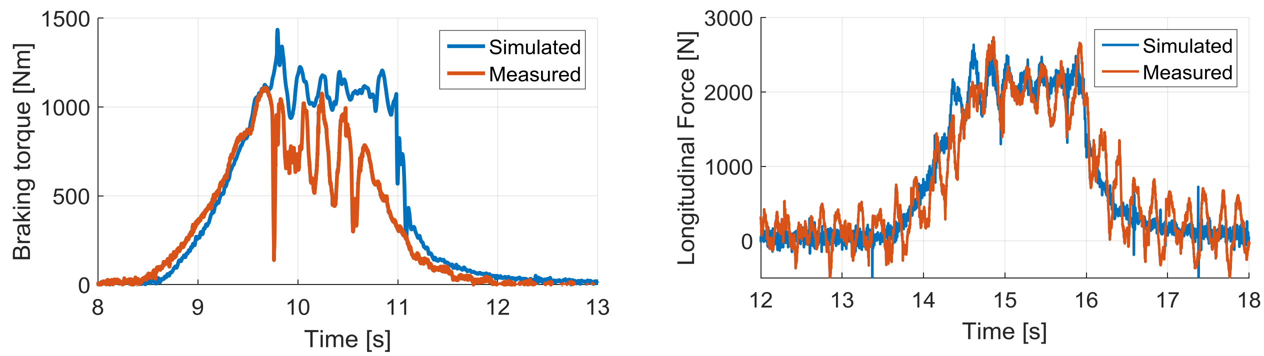
The peak from the measured data is closely matched by the peak from the simulation. This shows that the response of the trailer through the excitation forces on the tyres are modelled correctly. The next part of data from 11.8 to 12.1 seconds (Fig. 5b) shows that for both the simulated model and the experimental data the tyre loses contact with the ramp, having zero contact force. The experimental response of the trailer after the first peak seems too high as usually the vehicle dynamic loads are within a vicinity of 3-5 times static load. This could be due to the response from the towing vehicle which is pulling the trailer with an offset causing additional unwanted moments around the towing point. This extra excitation is also speculated to bring a mismatch of the measured data with the simulated data after 12.5 seconds. This is an extreme load case.



a) b)

Fig. 5. *Model validation tests showing wheel vertical force using both ramps: a) 10 km/h; b) 20 km/h*

The next set of data in Fig. 6 shows braking validation tests where the wheels were locked (ABS deactivated). The braking pressure was increased to 60 bar and kept constant for 1.5 second. The same pressure input was used into the ADAMS model and was converted to a braking torque on each of the wheels. The measured braking torque as compared to the simulated model, shows the same characteristic peaks. The magnitude of the peaks are different possibly because of different input conditions for braking. For the measured data, the braking torque is a result of the wheel slip, whereas the simulated braking torque is an input to the simulation, not necessarily a function of wheel slip. The braking torque should rather be measured from the simulation with the change in measured wheel speeds as an input to the simulated tests. As this is still a work in progress, the noise existent in the simulated data is still to be investigated and refined, however the comparison from the primary data is promising.



a) *b)*

Fig. 6. *Model validation braking tests without ABS a) Braking torque; b) Longitudinal Force*

The force characteristics show that the measured data is closely correlated with the simulated data according to the shape of the brake force characteristic and peaks in the braking stage (Fig. 6b). There are additional vibrational characteristics with the measured longitudinal force which will be investigated in future ABS braked tyre and road interaction analysis.

5. Conclusions and further investigations

This paper presents a tyre test trailer that was prepared and instrumented with the intention of future ABS analysis in terms of tyre and rough terrain interaction. The test trailer was validated by driving over synchronously placed ramps. The match of frequencies of dynamic force response between measured and simulated tests proves the model structure and obtained inertia values are correct. The differences in validation after entering the ramps were caused by towage movement and loss of contact with the road. The validation of the braking test without ABS proved that the used tyre model is adequate for simulating actual braking performance.

Vertical load and speed variation with different threshold values of ABS algorithm will provide an opportunity to improve tyre contact characteristics by analysing vibrations caused by ABS and road pavement fluctuations.

The prepared and validated Adams model with ABS control in Simulink now opens the opportunities to develop various braking research ventures not only experimentally, but also through simulation. The suspension elimination from the dynamic system concentrates the attention only to tyre and road interaction.

The braking pressure rise as a parameter relative with possible cause of resonance with tyre vibrations will also be investigated in future virtual and experimental researches. Additional vibrations due to rough terrain and ABS work as well as tyre side-slip induced angles on the test trailer can be investigated.

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