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Parameterisation and modelling of large off-road tyres for on-road handling analyses

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Abstract

Very few off-road vehicles are used exclusively under off-road conditions. Good off-road mobility dictates large high aspect ratio tyres with aggressive tread, low inflation pressures, soft suspension for good comfort as well as other vehicle parameters including large ground clearance and the related high centre of mass. This results in less-than-satisfactory vehicle handling and high rollover propensity on hard terrains at higher speeds. In order to simulate vehicle handling and roll over propensities, on non-deformable terrain, tyre characteristics in the form of side-force versus slip-angle curves, as well as suitable tyre models are required. For large off-road tyres these characteristics are not readily available. Tyre manufacturers either do not have these characteristics, or do not openly publish them. Similarly, the majority of tyre models have been developed and validated for passenger car tyres and their applicability to large tyres are unknown. The purpose of this study is to measure side-force versus slip-angle characteristics for a Michelin 16.00R20 XZL tyre – typically used on off-road trucks. The data is used to parameterise Fiala, UA (University of Arizona), Pacejka89 and FTire models. Simulation results are compared to both steady state and dynamic handling test results to determine the accuracy of these models.

Keywords: Large off-road tyre; Side-force; Slip-angle; Michelin XZL; Handling tyre model; Parameterisation; Pacejka89; Fiala; UA; FTire

1. Introduction

Air filled rubber tyres are used in many applications, ranging from bicycles, motorcycles, all terrain vehicles (ATV's), passenger cars, sport utility vehicles (SUV's), busses, trucks, tractors, military vehicles and aeroplanes. Very few off-road vehicles are used exclusively under off-road conditions. Good off-road mobility does however dictate large high aspect ratio tyres, with aggressive tread, low inflation pressures, soft suspension for good ride comfort as well as other vehicle parameters including large ground clearance and the related high centre of mass. This often results in less-than-satisfactory handling and high rollover propensity when operating on hard terrains. When travelling, these vehicles do not always encounter a straight path. They more often than not encounter curved paths and need to be able to negotiate them. When a tyre negotiates a curved path, it is its lateral characteristics that are currently at 'work'. This study focuses on measuring and modelling these lateral characteristics for large off-road tyres.

According to Haney (2003) "a modern pneumatic tyre is a complicated composite construction of strong, light polymer fibres held together in a matrix of visco-elastomeric polymers–rubbers". According to Pacejka (2006) the complexity of the structure and behaviour of the tyre is such that no complete and satisfactory theory has yet been propounded. Both of the above descriptions indicate that the tyre is a complex entity, and is an area that is still to be fully understood. It therefore forms an excellent basis for research and development.

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Nomenclature

$a_0 \ldots a_{13}$	lateral coefficients in 'Magic Formula'
B	stiffness factor in 'Magic Formula'
BCD	slope at zero slip-angle in 'Magic Formula'
C	shape factor in 'Magic Formula'
CD	product of C and D as used in 'Magic Formula'
C_{Fy}	lateral tyre stiffness
C_s	critical longitudinal slip
C_α	Fiala & UA tyre model cornering stiffness'
D	peak factor in 'Magic Formula'
E	curvature factor in 'Magic Formula'
F_y	tyre lateral force
F_z	tyre vertical force
LI	load index of tyre
l_n	contact patch length
S_h	horizontal shift in 'Magic Formula'
S_s	longitudinal slip ratio
$S_{s\alpha}$	resultant slip due to longitudinal slip and slip-angle
S_v	vertical shift in 'Magic Formula'
S_α	lateral slip due to slip-angle
$S_{\alpha c}$	critical lateral slip ratio
v	lateral tyre deflection
X_1	composite angle in 'Magic Formula'
α	tyre slip-angle
$\alpha_{critical}$	critical lateral slip-angle
γ	camber angle
μ	coefficient of friction
$\mu_{current}$	current friction coefficient of slip
μ_d	dynamic coefficient of friction
μ_s	static coefficient of friction
μ_x	friction coefficient in the longitudinal direction
μ_y	friction coefficient in the lateral direction
σ_α	relaxation length

To determine the tyre characteristics laboratory test rigs or mobile tyre test rigs are used. Laboratory type tyre testers comprise of Drum type (VMI Group, 2014), Belt type and full vehicle indoor test rigs (Flat-Trac® Tire Test Systems, 2005). An example of a mobile tyre tester is the TU-Delft tyre test trailer (Pacejka, 2006), used to test passenger and motorcycle tyres. Several examples of tyre testers utilised to characterise agricultural tyres on soft terrains are given by Kutzbach et al. (2009). This work was expanded on by Witzel et al. (2014) but still adresses only very low speed handling phenomena. One of the main significant differences between mobile and laboratory tyre testers is that mobile tyre testers utilise the actual road surface that the tyres are used on, whereas laboratory tyre testers utilise an artificially created road surface on a drum or on a steel belt.

For large off-road tyres the tyre handling characteristics are not readily available and are difficult to acquire. Researchers at the University of Michigan have published lateral and traction test results of three wide base truck tyres (Bogard and Winkler, 1991). Although the tested tyres had a low profile with an aspect ratio of 0.65 some of the tested tyres were designed to be used for on-road and off-road applications. The UPMTRI Flat-Bed Tire Tester was used to perform the measurements at low speeds. The tests were conducted at tyre inflation pressures of 8.2 and 9.1 bar respectively. Limited tests results are available that describe the lateral tyre behaviour of off-road tyres with a high aspect ratio and at relatively low inflation pressures.

2. Tyre models

Many tyre models exist that can potentially be used for handling analysis on hard surfaces. In this study, four popular tyre models, namely Fiala, University of Arizona (UA), Pacejka 89 and FTire, were parameterised to describe lateral tyre behaviour. This work uses the specific versions of the various models as implemented in the MSC ADAMS View software.

2.1. Fiala tyre model

The Fiala tyre model is a physics-based tyre model (ADAMS View HELP, 2012). The tyre carcass is modelled as a beam on an elastic foundation in the lateral direction. Elastic brush elements provide the contact between the carcass and the road. Analytical assumptions are derived for the steady state slip characteristics and these form the basis for calculating the longitudinal and lateral forces. The model assumes that the tyre contact patch is rectangular with a uniform pressure distribution. Camber effects are neglected in the Fiala tyre model. To determine the lateral force, Fiala defines a critical lateral slip angle as:

$$\alpha_{critical} = \arctan\left(\frac{3 * \mu_{current} * |F_z|}{C_\alpha}\right) \tag{1}$$

where the cornering stiffness, C_α, is defined as

$$C_\alpha = \left.\frac{dF_y}{d\alpha}\right|_{\alpha=0} \tag{2}$$

The current friction coefficient of slip, $\mu_{current}$, is a function of the static, μ_s, and dynamic, μ_d, friction coefficients as well as the longitudinal slip state of the tyre. The current friction coefficient is given by:

$$\mu_{current} = \mu_s - (\mu_s - \mu_d) * \sqrt{S_s^2 + \tan^2(\alpha)} \tag{3}$$

The lateral force is then calculated for the elastic deformation state, $|\alpha| \leqslant \alpha_{critical}$, by evaluating: