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Application of the rigid ring model for simulating the dynamics of motorcycle tyres on uneven roads

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ABSTRACT

Active control systems find their way into motorcycle technology for support of the rider, often aimed to enhance the safety without reducing driving pleasure. In order to develop these new systems in the virtual environment an extended description of the tyre behaviour is required. More specific, the higher order tyre dynamics need to be modelled for the full range of driving conditions. This includes large lean angles, combinations of lateral and longitudinal slip, and various road profiles. This publication describes the adaptations of a passenger car rigid ring model (i.e. SWIFT) for motorcycle tyres in order to simulate cornering on uneven roads. The main extensions are related to the quasi-static tyre behaviour for rolling over obstacles. Further, the effects on the high frequency response are discussed.

Keywords: motorcycle tyre model, uneven road simulation, tyre dynamics, rigid ring model.

1 INTRODUCTION

Due to the different construction and the large inclination angles that may occur, motorcycle tyres behave different from passenger car tyres. For this reason, the modelling techniques developed for passenger car tyres may not be directly applied. For instance de Vries and Pacejka [1] had adapted the well-known Magic Formula model for motorcycle tyres, which formed the basis for the widely used MF-MCTyre model of TNO [2]. Later Besselink et. al [3] adapted the original Magic Formula model for passenger car tyres in a different way to handle large inclination angles for both passenger car and motorcycle tyres resulting in a single Magic Formula for large camber angles, without making sacrifices with respect to accuracy for either normal passenger car or motorcycle tyres.

To be able to simulate the tyre dynamic behaviour at higher frequencies, shorter wavelengths (>0.2 m) and rolling over obstacles than is possible with a 'standard' Magic Formula tyre model, TNO and Delft University of Technology developed the SWIFT [4] tyre model. During the development of SWIFT, great emphasis was given to experimental validation using dedicated laboratory experiments with passenger car tyres. Motorcycle tyres were not considered in the development of SWIFT. However, the application of a simplified SWIFT-like rigid ring model for modelling motorcycle tyre sideslip behaviour on flat road was studied by De Vries and Pacejka [5].

Nowadays active control systems find their way into motorcycle technology for support of the rider, often aimed to enhance the safety without reducing driving pleasure. In order to develop these new systems in the virtual environment an extended description of the tyre behaviour is required. More specific, the higher order tyre dynamics need to be modelled for the full range of driving conditions. This includes large lean angles, combinations of lateral and longitudinal slip, and various road profiles.

To investigate the applicability of the SWIFT concept for motorcycle tyres a joint research project between TNO, Honda and Eindhoven University of Technology has been carried out. This research has lead to adjustments of TNO's MF-Swift (version 6.1) model so that it can be applied for motorcycle tyres. The main extensions concern the tyre-road contact under larger camber angles. In this paper the adapted MF-Swift model for motorcycles is described and comparisons with existing models (MF-Swift 6.1 and MF-MCTyre) are made to clarify the added value of the new model.

In section 2, the MF-Swift model and the extensions made for motorcycle tyres are described. Further, differences with regard to the widely used MF-MCTyre model are explained. Next, the evaluations of the different models are described. Experiments for the tyre only are discussed in section 3, and for uneven road motorcycle simulations in section 4. Finally the conclusions of the paper are summarised in section 5.

2 MODELLING CONCEPTS

A schematic view of the MF-Swift model is shown in Figure 1. The important elements of the model are:

- Steady-state slip model;
- Contact and carcass compliance model;
- Rigid ring;
- Obstacle enveloping model.

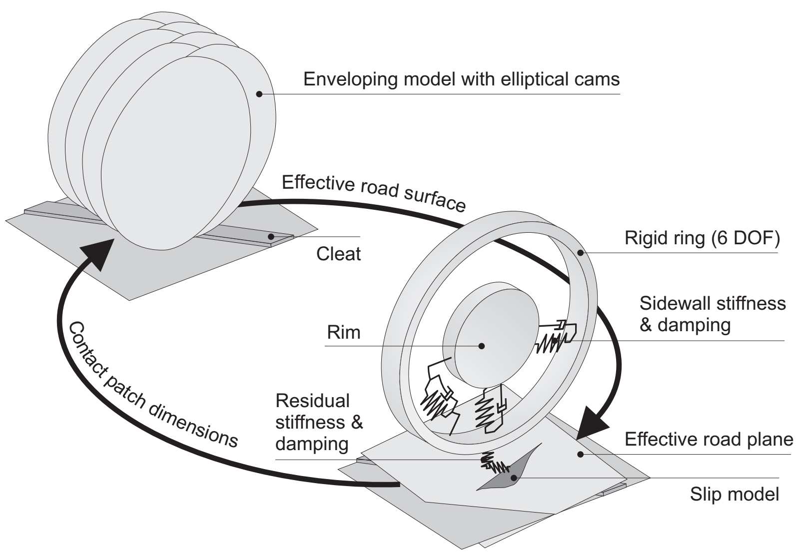


Figure 1. Schematic view of the MF-Swift model.

2.1 Steady-state slip model

To describe the steady-state slip forces and moments as function of longitudinal slip, side slip, turn slip, camber, vertical load and inflation pressure the well-known Magic Formula model of Pacejka is used. Basically, this semi-empirical model consists of a set of equations that are parameterised by fitting these on steady-state slip measurements. In the latest MF-Swift model (version 6.1), the Magic Formula equations described in Besselink et. al [3] are used. These Magic Formula equations can be used for modelling both passenger car and motorcycle tyres, and thus no modifications are needed with regard to this element. In MF-MCTyre the motorcycle Magic Formula equations of De Vries and Pacejka [1] are used.

2.2 Contact and carcass compliance model

The function of the contact and carcass compliance model is to obtain the normal force, axle height, effective rolling radius and the slip velocities of the contact patch. The carcass compliance not only determines the loaded and effective rolling radius of the tyre model, but also contributes to the relaxation behaviour [6]. The tyre force does not respond instantaneously to changes in slip and camber, but a certain distance needs to be travelled before the steady-state levels of force and moment are reached. The flexibility of the carcass accounts for the major part of the overall relaxation effects. The compliance of the contact patch accounts for the remaining part. Finally, from the deformation velocities of the carcass the slip quantities that are input to the Magic Formula are obtained.

Below the adaptations for motorcycle tyres of MF-Swift 6.1 are explained. The main differences are apparent under large(r) camber angles.

Normal force and effective rolling radius

The different concepts for calculating the normal force *Fzw* and the effective rolling radius are depicted in Figure 2. In the MF-Swift model, the contact point is determined by the intersection of wheel plane, road plane, and a plane through the wheel spin axis that is normal to the line of intersection of the wheel and road plane. From the deflected radial spring that is positioned in the wheel plane the normal force is obtained. The effective rolling radius is obtained from an empirical equation [7] and it equals the tyre free radius if the normal load *Fzw* equals zero, regardless of the inclination angle.

In MF-MCTyre the cross-section of the motorcycle tyre is approximated with a circle. From the intersection of this circle with the road surface the tyre deflection is obtained. Further, a linear stiffness *Cz* that is normal to the road surface is used to obtain the normal force. Finally, the effective rolling radius is obtained from the same empirical equation as used in MF-Swift.

Instead of approximating the cross-section of the motorcycle tyre with a circle, an ellipse is used in the adapted model to describe this cross-section more accurately. From the intersection of the ellipse with the road surface the tyre deflection is obtained. Further, both the radial *Cz* and lateral stiffness *Cy* of the tyre are used to determine the normal force. Finally, the empirical relation for the effective rolling radius is adapted so that at zero normal force, the effective rolling radius equals the radial distance from the lowest point of the ellipse to the wheel centre (*Re*0 in Figure 2).

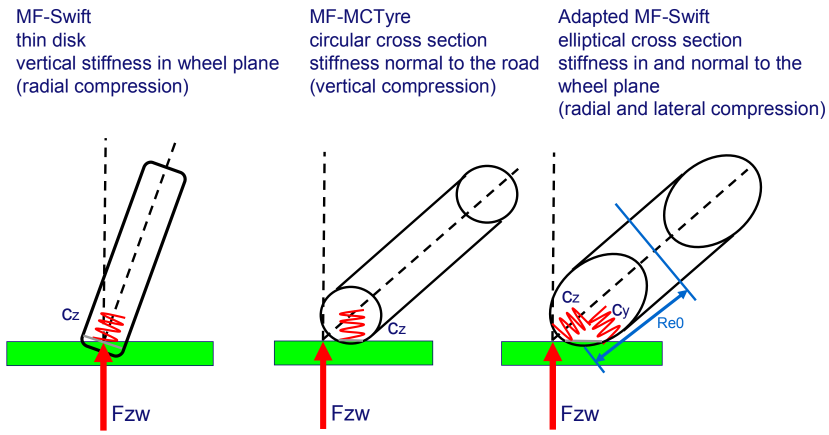


Figure 2. Comparison of concepts for calculating the normal force *Fzw* and effective rolling radius *Re*.

Slip velocity

The carcass deformation velocities have to be considered for calculating the slip of the contact patch. In the MF-Swift model the lateral carcass compliance consists of the lateral stiffness of the rigid ring model, the camber stiffness of the rigid ring model and a residual lateral stiffness. In MF-Swift the residual stiffness is defined in tangential direction with regard to the road plane. As can easily be imagined when considering Figure 3, this approach is only justified for relatively small camber angles. In the adapted model, the residual stiffness is defined normal to the belt (i.e. rigid ring) plane, see Figure 4. Finally, in both models the compliance of the contact patch is described with a first order relaxation system.

In the MF-MCTyre model the relaxation behaviour is modelled in a different way. Instead of taking the carcass compliances into account a single first order relaxation system is used.

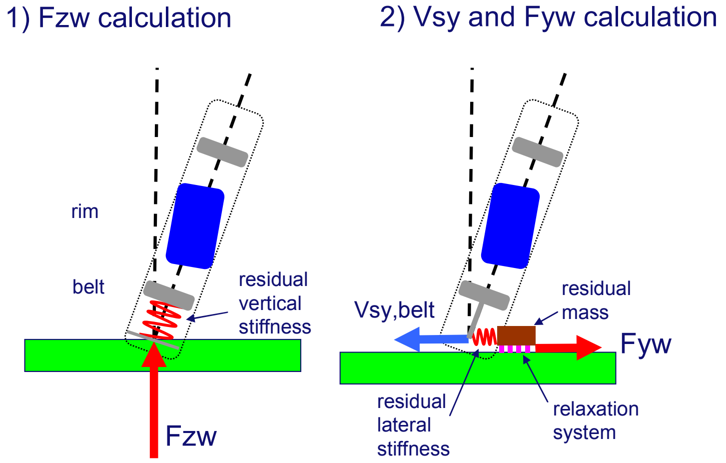


Figure 3. Concept of normal force *Fzw* calculation (left), and slip velocity *Vsy* and transient lateral force *Fyw* calculation (right) of the MF-Swift model.

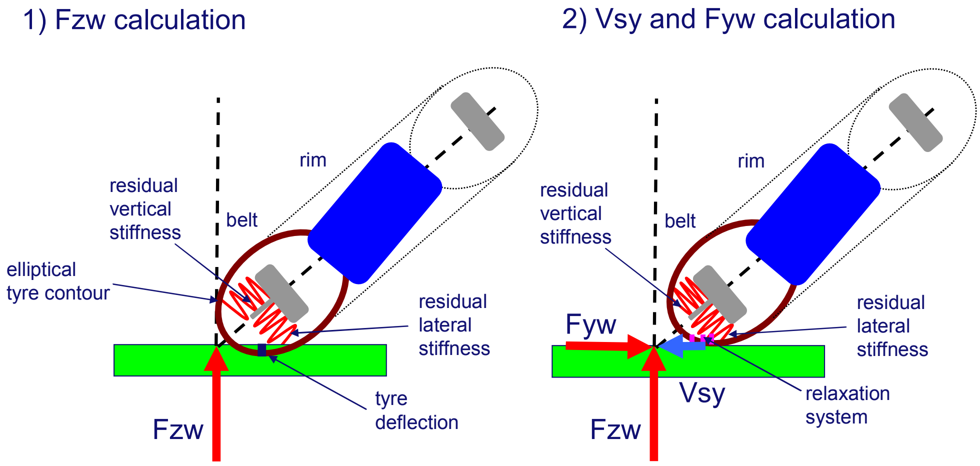


Figure 4. Concept of normal force *Fzw* calculation (left), and slip velocity *Vsy* and transient lateral force *Fyw* calculation (right) of the adapted model for motorcycle tyres.

2.3 Rigid ring

When considering the primary eigen modes of a tyre it appears that the deformations of the tyre belt itself can be neglected [4]. Consequently, the tyre belt is modelled as a rigid body, which is elastically suspended with respect to the rim for all six degrees of freedom. Residual springs are introduced between the tyre belt and the contact patch to ensure that the overall stiffness of the rolling tyre is correct. No modifications have been done to this element for the adapted model for motorcycle tyres. Note that in MF-MCTyre the rigid ring is not considered.

2.4 Obstacle enveloping model

For the model described so far, the contact between tyre and road is modelled as a single point. This approach cannot be applied (directly) on short wavelength obstacles, because of the considerable local tyre deformations. This effect is referred to as the tyre enveloping behaviour [8].

To incorporate this tyre enveloping behaviour in the MF-Swift model, the concept of the effective road surface is used. The consideration behind this effective input is that it is assumed that the quasi-static forces of a tyre model with a single-point contact on the effective road surface is similar to the quasi-static forces of the real tyre on the actual road surface. As a result this effective road surface can be reconstructed from the quasi-static tyre force and the tyre stiffness properties for single point contact. Furthermore, the assumption is made that the tyre contact zone dynamically deforms in the same way as it does quasi-statically and that, consequently, local dynamic effects in the contact area can be neglected; the rigid ring takes care of the dynamics.

In MF-Swift an obstacle enveloping model, consisting of elliptical cams that touch the actual road surface, is used to generate the effective road input. This effective input consists of a plane height, plane slope and banking (road camber). With this model it is possible to calculate the effective road surface for arbitrary 3D road unevenness [8]. Basically, in the contact area a grid of elliptical cams that represent the tyre geometry is used to sense the road undulations, see Figure 1. From the positions of these cams we can calculate:

- The vertical position of the effective road plane by taking the average of the vertical coordinates across the width for both the front and rear row of cams.
- The slope of the effective road in the driving direction by calculating the average angle across the width of the tyre contact patch for the front and rear row of cams.
- The slope transverse to the driving direction (road camber) by calculating the average angle across the length of the tyre contact patch for the left and right row of cams.

It can be noted that the elliptical cams are only required on the outside contour of the contact patch. Furthermore, the contact patch dimensions (especially the contact length) change as a function of vertical load. This interaction is schematically shown in Figure 1.

With regard to MF-Swift the following modifications have been done for motorcycle tyres:

- The enveloping model is positioned at the tyre road contact patch instead of straight below the wheel centre.
- Two enveloping effects have been modelled to better represent the enveloping behaviour for motorcycle tyres. These effects consider attenuation of the effective height and slope compared to passenger car tyres.

Finally, it is remarked that the obstacle enveloping model is not available in MF-MCTyre.

3 TYRE EXPERIMENTS

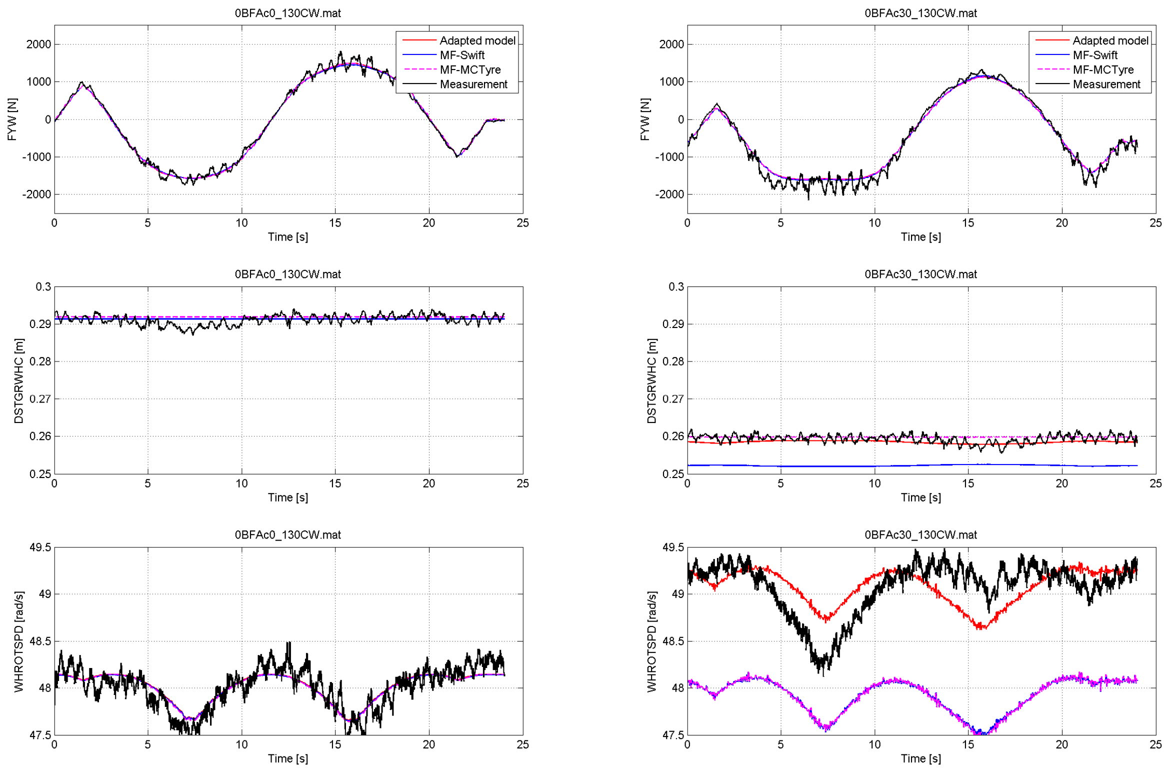
This section presents simulation results of tyre behaviour in order to compare the performance of the adapted model to MF-Swift and MF-MCTyre. The model parameters have been derived from a set of experimental data using TNO's MF-Tool software [2]. The simulation results are compared with some of the experiments that were used for parameter assessment.

3.1 Axle height

The comparison of axle height description in the tyre models is done by simulation of an experiment in the test sequence for Magic Formula parameter assessment. In the experiment the vertical load is controlled at a constant level and the inclination angle of the wheel is fixed. By steering the measurement tower a slip angle is applied to the wheel. The TNO Tyre Test Trailer and measurement tower are depicted in Figure 5.

Figure 5. TNO Tyre Test Trailer and test tower for motorcycle tyres.

Figure 6 shows the comparison with measurement data for zero inclination and an inclination angle of 30 degrees. For zero inclination angle the axle height (DSTGRWHC) of MF-MCTyre is slightly deviating due to its linear description of the tyre force-deflection characteristic compared to the quadratic description used in the MF-Swift model. The lateral force is identical for all tyre models as these all use the Magic Formula model parameterised on the same force and moment slip data. For the zero inclination condition the wheel rotation speed (WHROTSPD) is identical for all models, since the descriptions for the effective rolling radius are identical in this case.



inclination angle 0 degrees

inclination angle 30 degrees

Figure 6. Comparison of tyre models with measurement results of the TNO Tyre Test Trailer.

For an inclination of 30 degrees, we observe again that the lateral force from all models is identical. Concerning the axle height we observe that MF-MCTyre and the adapted model better match the measured signal. In contrast to those models, MF-Swift does not consider the tyre cross-section shape and as a result the deviation with the measurement is considerable. Note that the adapted model shows a similar variation in axle height as the measurement. As MF-Swift also shows a variation in axle height, it is concluded that this effect is the result of the rigid ring component in the model. The rigid ring is not contained in MF-MCTyre, resulting in an axle height invariant of the lateral tyre force. Finally, the wheel rotation speed is most accurately described by the adapted model. The results for MF-MCTyre and MF-Swift virtually coincide and show a larger deviation with the measurements.

3.2 Obstacle passage

The obstacle passage simulation is aimed to compare the tyre models concerning the road contact and enveloping models. The simulation results are compared to measured forces from experiments that were carried out on a drum with fixed spindle position.

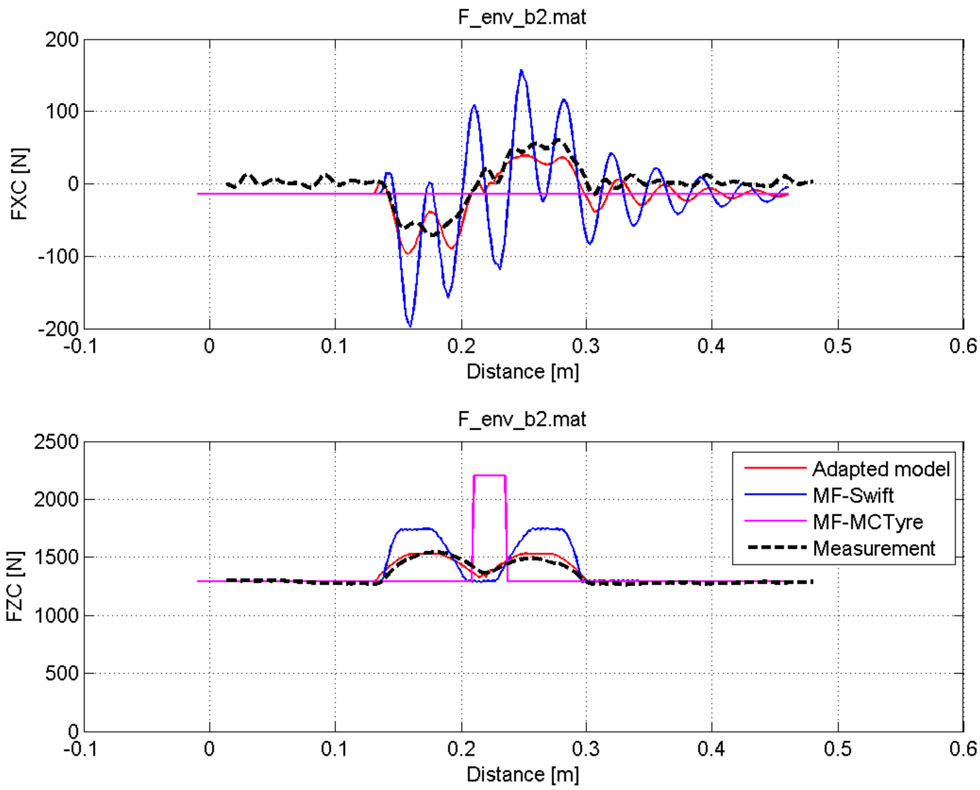


Figure 7. Low speed obstacle response; longitudinal spindle force FXC (top) and vertical spindle force FZC (bottom).

Figure 7 shows a comparison of the force response from the different tyre models to measured forces on a cleat obstacle at very low speed. The displayed force response of MF-MCTyre is a good indication of the obstacle position and shape. For MF-Swift the vertical force increase during passage of the obstacle is about 50% of the increase for MF-MCTyre. The measured vertical force signal is represented well by the adapted model, which is achieved by extension of the enveloping model concept compared to MF-Swift. Also the longitudinal force response is most accurate for the adapted model. Note that MF-MCTyre shows no longitudinal force component during obstacle passage.

As a validation the results of the tyre models are compared to measurements from a high speed experiment in Figure 8. As can be seen, the high speed vertical force response of both MF-Swift and MF-MCTyre are too high, similar as for the low speed experiment. The tyre vibrations are not observed for MF-MCTyre as it lacks the rigid ring component. The improvements of the adapted (enveloping) model compared to MF-Swift are also observed in the high speed cleat impact response. The resonance frequencies of both rigid ring models coincide with the experimental results, showing that the rigid ring model can represent the dynamics of the motorcycle tyre. Note that this resonance frequency is close to 200 Hz, while for passenger car tyres it is typically below 100 Hz.

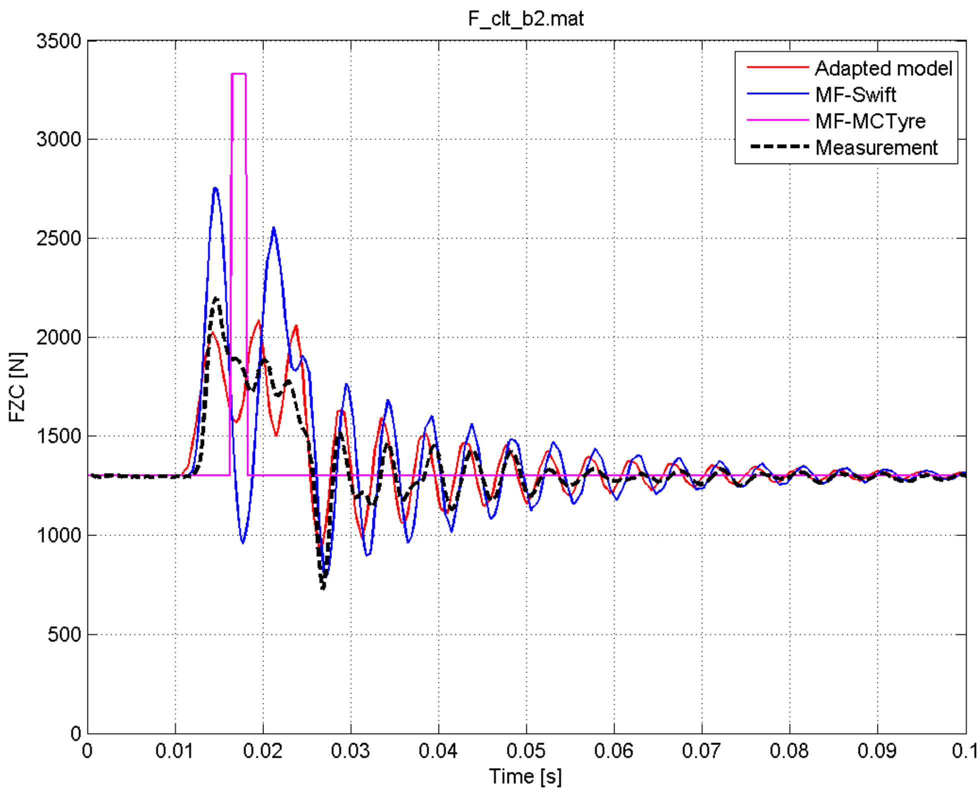


Figure 8. Response on cleat of different models; vertical spindle force FZC is shown.

4 UNEVEN ROAD SIMULATIONS

To assess the influence of the tyre model changes on the motorcycle response when driving over obstacles, simulations have been carried out with a multibody motorcycle model equipped with the different tyre models. The model is schematically shown in Figure 9.

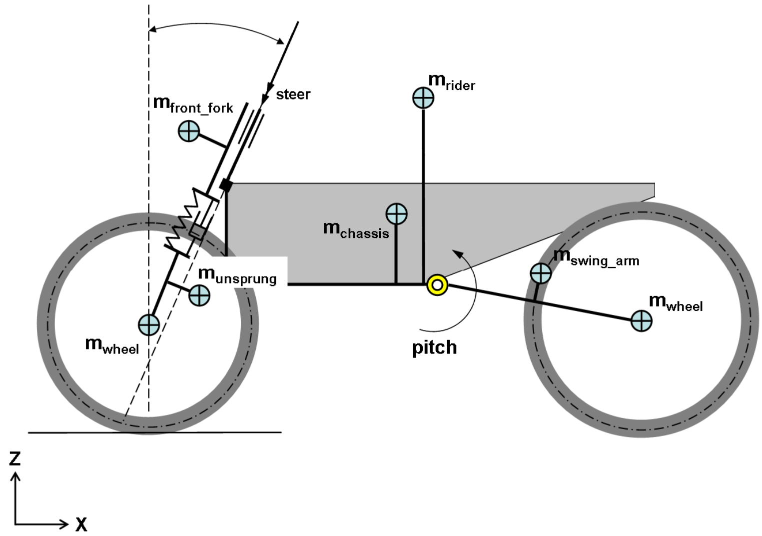


Figure 9. Schematic representation of the multibody motorcycle model.

Since in the previous section it is shown that MF-MCTyre is not suitable for obstacle passing, simulations are only compared for the MF-Swift model and the adapted model. Figure 10 and 11 show the simulated spindle forces of the front wheel in vertical and longitudinal direction respectively while driving over a 10x25 mm obstacle with a velocity of 35 km/h. As can be observed from these figures – and could be expected from the tyre only obstacle passing experiments – the forces of the simulation in which the adapted model is used are considerably lower than the forces of the simulations with the MF-Swift model. Consequently this example demonstrates the potential improvements of the adapted model for predicting the forces of motorcycles on uneven roads.

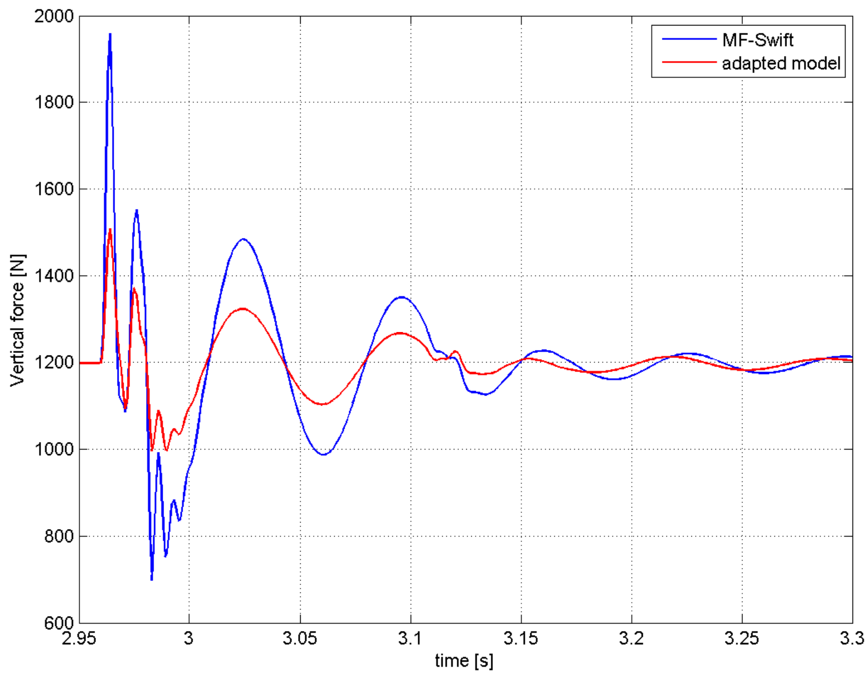


Figure 10. Simulated vertical front wheel spindle forces.

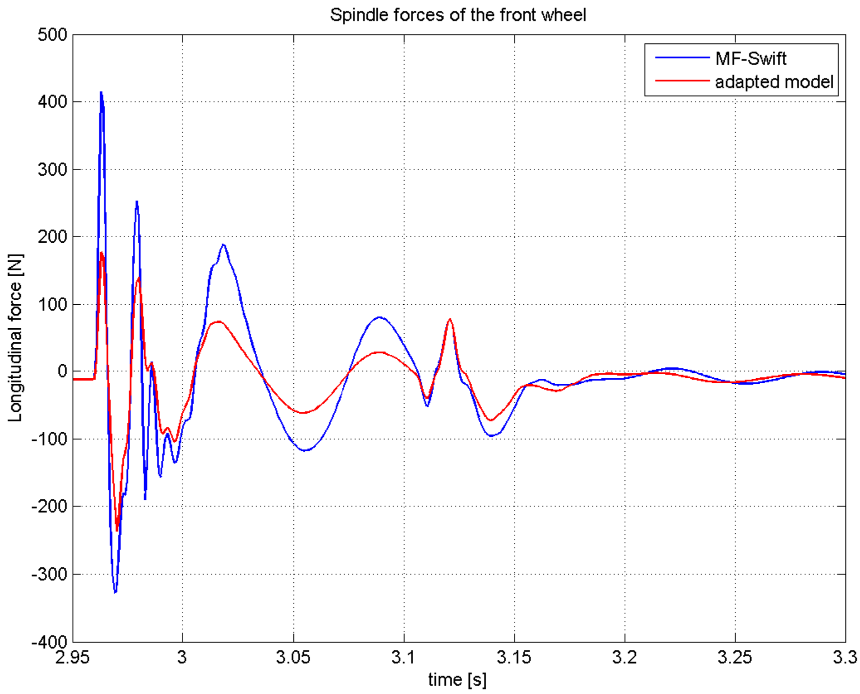
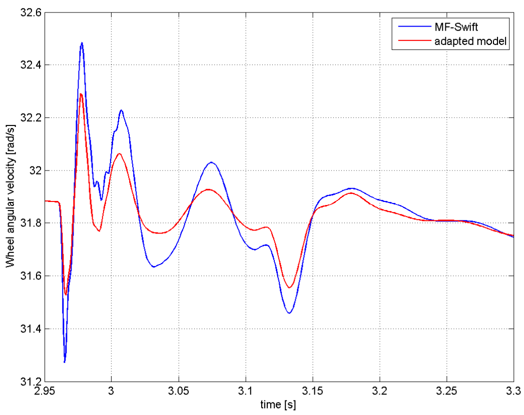
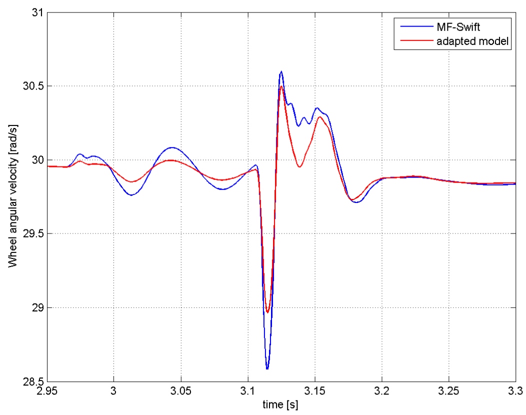


Figure 11. Simulated longitudinal front wheel spindle forces.

Apart from the comfort and durability aspects the braking performance is affected by road unevenness. Modern motorcycles are equipped with ABS, and theses systems mainly use wheel rotation speed in their algorithm. The results in Figure 12 show the simulated wheel rotation speed during passage of the obstacle. As can be seen the results of the adapted model are clearly different compared to MF-Swift. For the development of braking applications it is therefore also recommended to use the adapted simulation model.



Front wheel



Rear wheel

Figure 12. Wheel speed during obstacle passing.

5 CONCLUSIONS

In this paper a rigid ring model for motorcycle tyre simulations is described and compared with an existing rigid ring model for passenger car tyres (MF-Swift) and a Magic Formula model for motorcycle tyres (MF-MCTyre). It is shown that an accurate tyre cross-section description is required for accurate representation of axle height and wheel rotation speed. The enveloping behaviour of motorcycle tyres is clearly different from passenger car tyres, and an extended method clearly shows improved response for obstacle simulations. The rigid ring approach not only results in an accurate description of the main tyre resonances that occur on uneven road, but it also seems that changes of axle height due to variations of lateral force are captured using the rigid ring approach.

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