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A MULTIBODY TOOL FOR THE OPTIMIZATION OF THE SUSPENSION SETUP AND GEOMETRIC LAYOUT OF RACING MOTORCYCLES

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ABSTRACT
In races, it is essential to adjust the motorcycle setup to different tracks, weather conditions and rider requirements. Vehicle adjustments are usually based on empirical know-how since decisions should be taken quickly and under pressure. Classical multibody tools cannot be adopted for this purpose because they are very complex to manage and simulations are time consuming.
This paper presents a non-conventional multibody software specifically designed for this purpose that allows to easily manage and optimize motorcycle parameters such as suspension characteristics, adjustable plates, etc. Some examples of geometry and suspension optimization are presented. A simulation of a braking manoeuvre shows also the genesis of the chatter vibration; phenomena that can compromise the motorcycle performance.

INTRODUCTION

A general multi-body code for studying the motorcycle dynamics was developed.
This tool, called FastBike Race, contains a detailed multibody model of the motorcycle, including non-linear suspensions, a tire model that works at large camber angles and include the geometry and compliance, a flexible chain transmission, frame compliance. The motorcycle model is optimized and makes it possible not only to make time simulations, but also to compute steady state (i.e. inverse dynamics) and stability analysis at different speeds, longitudinal and lateral accelerations.
Since the motorcycle model requires many parameters, data input is organized in two different layers. In the first layer, designed for the vehicle development, all the model features are available to the user, which may specify the geometry, inertia, structural compliance, tire properties, etc. At this level many analysis tools are available (steady state, stability, braking, cornering, kick-back, etc.). A second simplified layer is designed for the pit lane: in this layer most motorcycle parameters are hidden, while only adjustable ones are available (e.g. suspensions preload and stiffness, adjustable plates). The analysis tool includes trim and steady state calculation, suspensions optimization, chatter analysis.
The peculiarity of trim and steady state analysis is that solution are found almost instantaneously. Indeed, the solution is obtained by solving the equilibrium equations instead of by integrating the dynamic equations as multibody software normally do.
In the setup optimization the user first sets its trim target (e.g. wheelbase, normal trail, rake angle, suspensions travel). Then it defines the adjustable parameters (e.g. spring preload and stiffness, length of the rod linkage, size of adjustable plates), finally the software optimizes these parameters. The optimization process requires a lot of trim evaluations at different speeds and accelerations, anyway the results is available in a short time due to the computation efficiency of the model and inverse dynamics approach.

The appropriate modelling of the powertrain makes it possible to simulate the presence of the chatter, a self-excited vibration well known on race motorcycles. Chatter is unwanted since the vibration of the rear and front unsprung could reach 5-10 g at a frequency of 17-22 Hz. This software is actually under testing by a racing team involved in the Italian Speed Championship (CIV).

THE MOTORCYCLE MODEL

The motorcycle model includes all features, which are relevant to reproduce the real dynamic behaviour of the vehicle. Particular attention has been posed on the modelling of tires (as explained in the above section) and suspensions. The chain transmission is also described in detail.

The motorcycle consists of a system of six rigid bodies, as follows:

- the rear assembly, which includes the chassis, the engine and the tank;
- the front assembly, which is comprised of the handlebars, the triple clamps, the accessories connected to the handlebars, and the fork sprung parts;
- the rear unsprung mass, which comprises the swingarm and the rear brake caliper;
- the front unsprung mass, which comprises the unsprung part of the forks and the front brake caliper;
- the rear and front wheels, which comprise tires, the brake discs and other rotating parts.

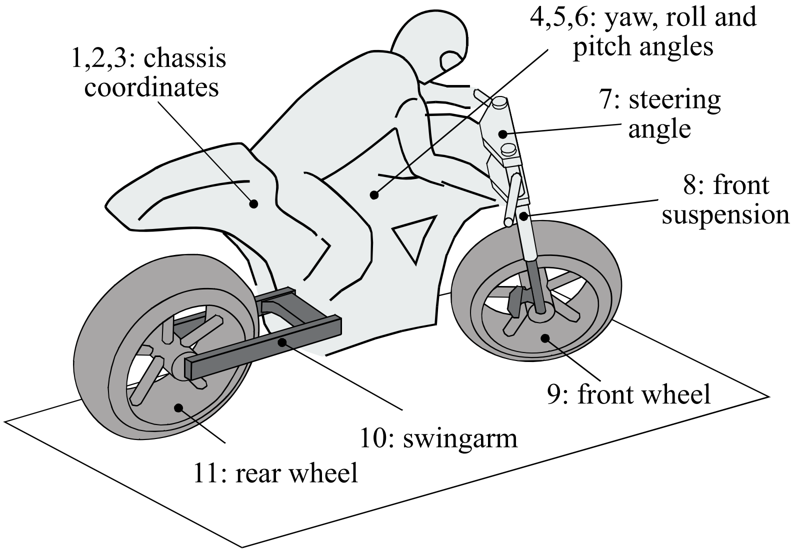

Figure 1: Degrees of Freedom of the Motorcycle Model

Both the rider and the passenger are assumed to be rigidly attached the rear assembly. The bodies are connected to each other in order to reproduce the most important degrees of freedom of a typical motorcycle. The front and rear frame are joined by a revolute joint, which is the steering mechanism. The front wheel and the front unsprung masses are free to translate with respect the front frame, reproducing the telescopic motion of the front fork. A revolute joint allows the swingarm, the rear wheel, and the rear unsprung mass to rotate around the swingarm pivot. Two revolute joints allow the spinning motion of both wheels. The overall number of degrees of freedom is eleven, as shown in the Figure 1. More details may be found on (1) and (2)

The compliance of front fork, frame and swingarm, as well as the mobility of rider and passenger are being modelled. At this stage these features are included in the stability linear analysis (3), but they are not yet available for non-linear simulation.
This schematization of the vehicle is adequate for reproducing dynamic phenomena up to about 15-20 Hz, i.e. it is adequate for simulating different conditions, such as steady cornering, lane change and slalom manoeuvres, weave and wobble mode excitation. A comparison between simulations and experimental.
The mathematical model has been entirely derived in symbolic form by the MBSymba (4) and the natural coordinates approach, then it was implemented in a Fortran code named FastBike. This approach has the disadvantage of being time consuming in the development and update phases , but it leaves the complete control on the model. Moreover, the achieved high computational efficiency makes it possible the real-time integration. This characteristics exploited in the University of Padova motorcycle simulator (5). Moreover, the availability of the mathematical model makes it possible to rearrange the equations to quickly carry out further kinds of investigations such as steady state analysis, modal analysis and frequency transfer functions calculation, as reported in the next paragraphs.
The software is completed with an user-friendly graphical interface for managing vehicle characteristics and planning simulations.

Tire model

From a physical point of view, tire forces and torques arise from the distribution of stresses on the contact patch between the tire and the road. In this model the centre of the contact patch is assumed to be the actual contact point and tire forces are applied on it, as shown in figure 2. More in detail, tire load N acts along the Z axis, which corresponds to the normal direction of the tire-road contact surfaces; the longitudinal force S acts along the X axis, which is perpendicular to both the Z axis and the wheel spin axis; the lateral force F acts along the Y axis, which is perpendicular to both the X and Z axis. A rolling resistant moment My and a yaw moment Mz are further included, whereas no overturning moment Mx is necessary since the tire load is applied on the actual contact point.

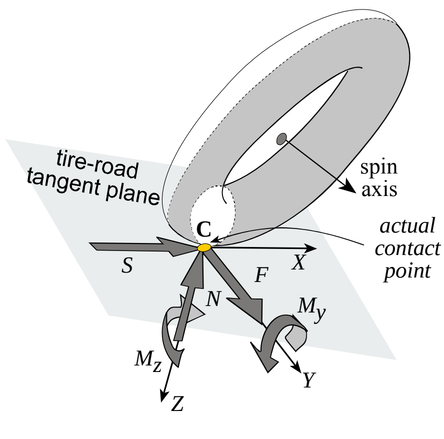

Figure 2: Tire forces and torques applied on the actual contact point

Tire contact forces and torques are due to the sliding of the tread rubber localized in the contact patch area. This physical behaviour is described by means of the well known “magic formula” (6) (7),where the longitudinal force S and lateral force F are described as a function of the tire load N, the longitudinal slip κ, the sideslip angle λ.and the tire camber angle α:

$$S = S_{magic}\left(\kappa, \lambda, \alpha, N\right)$$
$$F = F_{magic}\left(\kappa, \lambda, \alpha, N\right)$$

Sliding forces are transmitted to the rim through the tire carcass, which is deformable. The behaviour of the carcass is here modelled by means of two translational spring-damper assemblies, which act along the lateral and radial wheel axis plus a torsional spring-damper assembly, which acts around the spin axis. This approach is very effective because the radial and lateral compliance of the tire are almost independent from the camber angle.
It is well known that in transient condition there is a delay between wheel motion (i.e. superimposed tire kinematics) and tire forces. The physical cause of this behaviour is due to the carcass compliance, therefore the properly dynamic behaviour of tires is mathematically described by coupling the equations of the sliding forces with the equations of the elastic forces, as follows:

$$S_{magic}\left(\kappa, \lambda, \alpha, N\right) = S_{elastic}\left(\xi, \dot{\xi}\right)$$
$$F_{magic}\left(\kappa, \lambda, \alpha, N\right) = F_{elastic}\left(\zeta_R, \zeta_L, \dot{\zeta}_R, \dot{\zeta}_L, \alpha\right)$$

More details about the tire model are available in (8)

<u>Suspensions model</u>

The FastBike Race code contains full parametric suspension models; the costumer can choose the type of geometry of the suspension: telescopic fork, telelever, duolever, swingarm, paralever. Figure 3 shows the geometrical characteristics of the different type of suspensions. Springs are fully modelled including pneumatic effects; shock-dampers are described by different polynomial functions between rebound and compressions. Linkages kinematics is described by polynomial function.

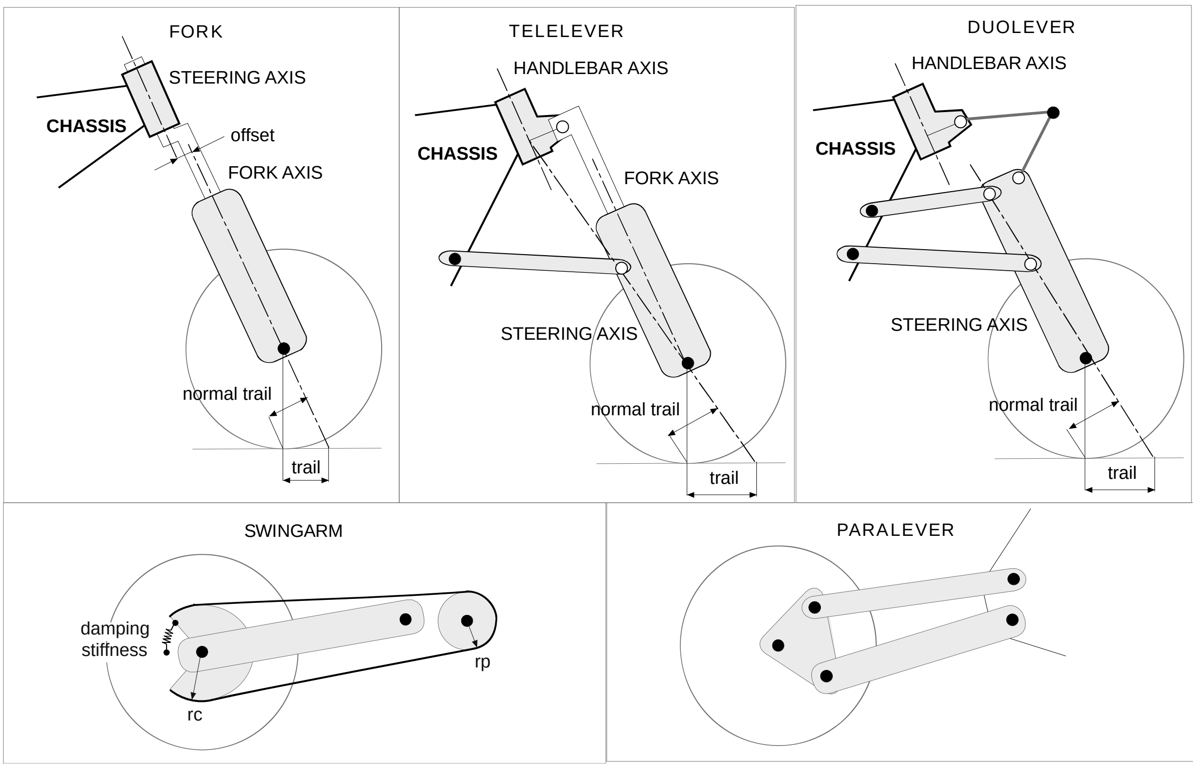

Figure 3 : Different types of suspensions

SIMULATION

Braking manoeuvre

The following diagrams illustrate the dynamic behaviour of a sport motorcycle varying the longitudinal deceleration and the lateral acceleration, while the forward velocity is maintained constant and equal to 60 m/s.
The upper figures show the suspension travels: the length of front suspension decreases as deceleration decreases (i.e. as braking increases); whereas the rear shock-absorber length is almost constant with deceleration, and decreases as lateral acceleration increases.
The left-lower figure shows the absolute normal trail, i.e. the minimum distance between the front contact point end the steering axis.
The right-lower figure shows the almost linear dependency between the wheelbase and the front suspension travel: wheelbase decreases as the length of the front suspension decreases.

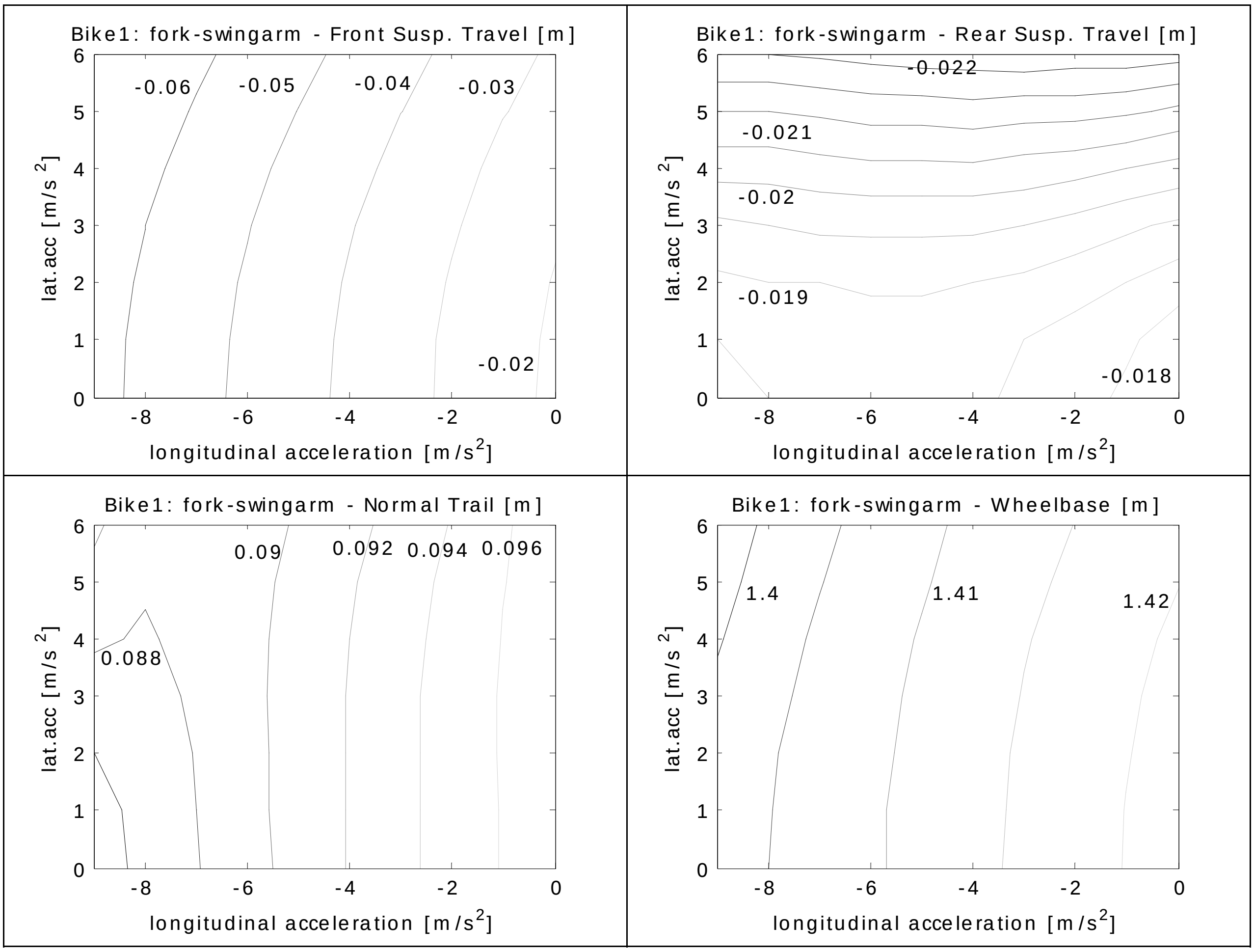

Figure 4 : Dynamic behaviour of motorcycle equipped with telescopic fork and swingarm during braking in turn

Acceleration manoeuvre

The acceleration simulation shows the dynamic behaviour of a sport motorcycle varying the longitudinal acceleration and the lateral acceleration, while the initial speed is assumed equal to 10 m/s in all cases.
The left-upper figure shows the transfer angle witch corresponds to the ratio between the motorcycle centre of mass height and the wheelbase. The value decreases as the lateral acceleration increases, as consequence of the C.o.G. height reduction with the roll angle.

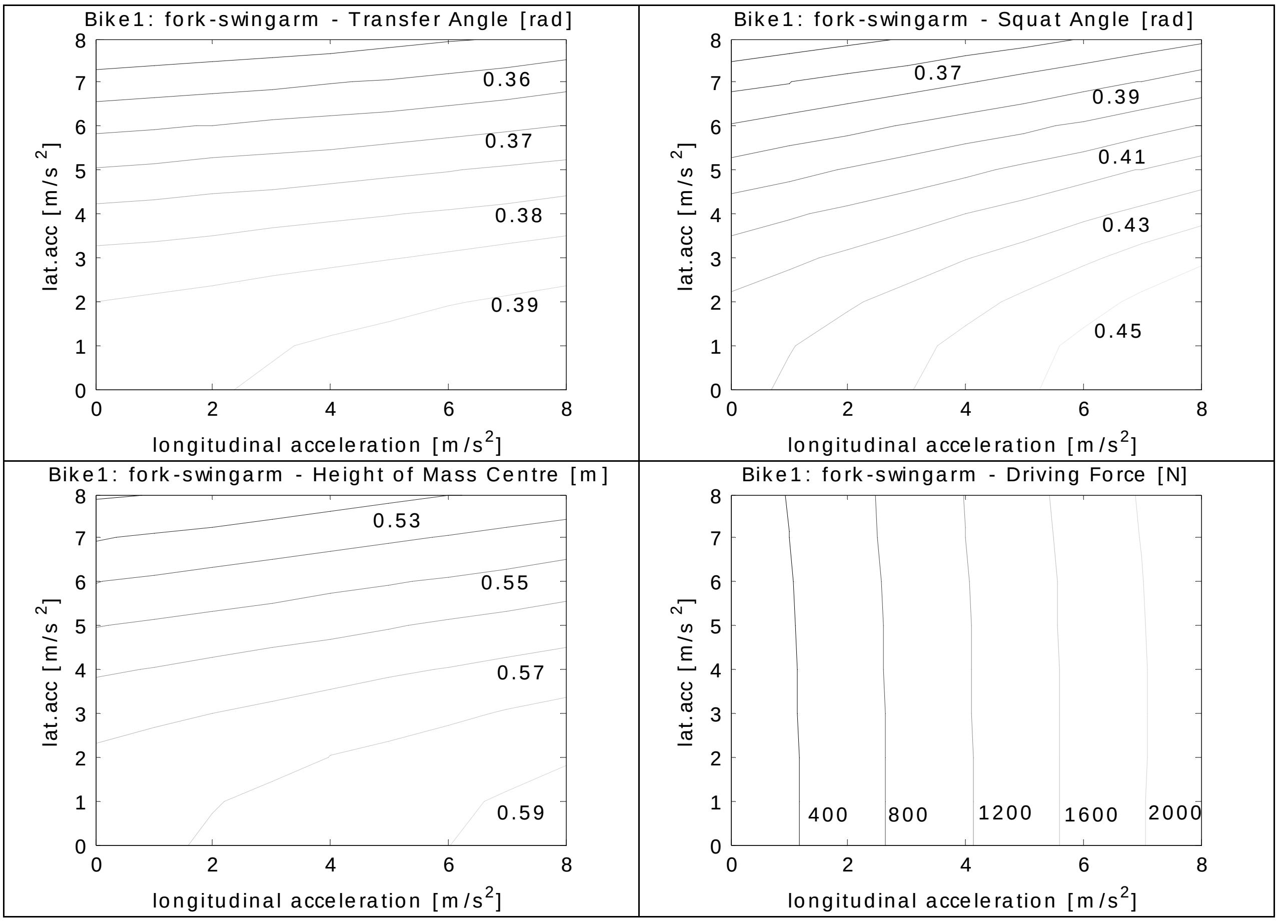

Figure 5 : Dynamic behaviour of sporting motorcycle in turn during acceleration

The left-lower figure shows the variation of the height in curve during an acceleration. The height increases as the forward acceleration increases, whereas decreases as lateral acceleration increases.
The right upper figure illustrates the squat angle. It is immediate to note that squat angle values are grater than transfer angle values in any of the considered dynamic condition. This results in an elongation of the rear suspension during the acceleration phase.

Chatter phenomenon

The chatter of motorcycles appears during braking and consists of a vibration of the rear and front unsprung masses at a frequency in the range of 17–22 Hz. This vibration can be very strong with unsprung masses acceleration of 5–10 g. The chatter is an auto-excited vibration and this fact explains why it appears suddenly as the auto-excitation mechanism is generated. The bike simulated is a 125cc racing motorcycle. Figure 6 illustrates a straight-running braking manoeuvre with a deceleration of 5.7 m/s^2, and speed varying 50 to 25 m/s; braking is equally parted between front brake and engine brake. Chatter is evident in Figure 6a, where the acceleration of the front unsprung mass reaches 5 g and the acceleration of the rear unsprung mass reaches nearly 20 g. The phenomenon starts at about 37 m/s at the rear wheel and then moves toward the front wheel. The vibration amplitude of the rear suspension is always greater than that of the front one (Figure 6b). Figure 6c underlines that the contact force fluctuates at 19 Hz; Figure 6d shows that the engine spin rate is opposite in phase with respect to the rear wheel spin rate.
More details about chatter may be found in (9) and (10)

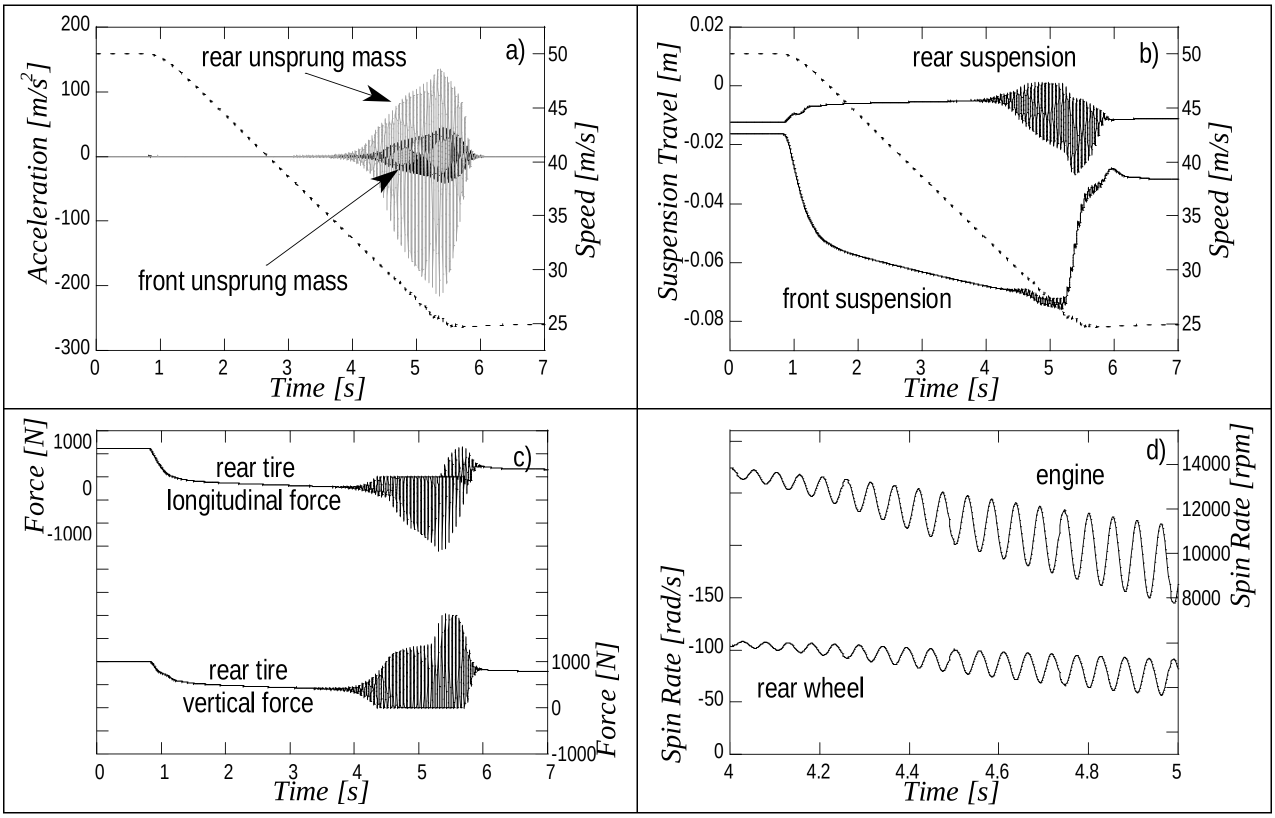

Figure 6 : Braking from 50 to 25m/s with a deceleration of 5.7m/s2 (50% front brake/50% engine brake).

OPTIMIZATION

The setting of the motorcycle trim on the track is a laborious process that is carried out according to riders experience and acquired telemetry.

The geometrical parameters that are varied to adjust the dynamic behaviour of motorcycle according to the characteristics of circuit (fast track, slow, presence of chicanes, parabolic curves) are the caster angle, the pitch angle, trail ,the squat angle, and suspensions setting.

Small value of caster angle and trail favour motorcycle handling: the curve entering manoeuvre is easier and the motorcycle is more reactive in chicanes; long wheelbase conversely gives more stability during fast curves; the squat angle defines the trim of motorcycle during acceleration.

Three phases are clearly defined during turning manoeuvre: entrance, middle and exit.

The **entrance** starts when the rider switches off the throttle and starts braking, and finishes when the motorcycle follows the trajectory impose by the rider. In this phase the front

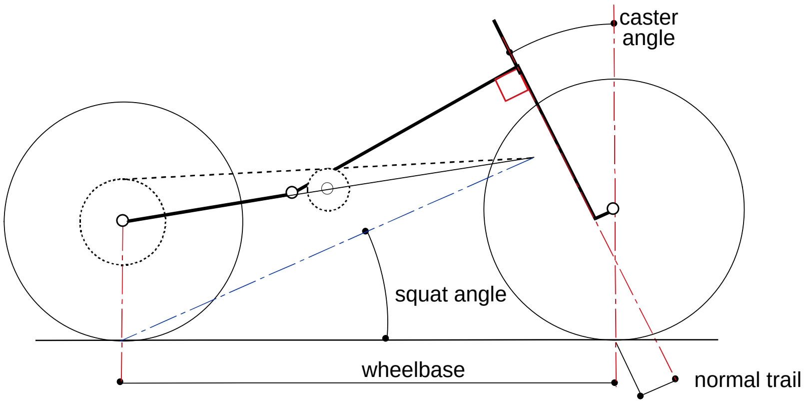

Figure 7 : Optimization dependent variables

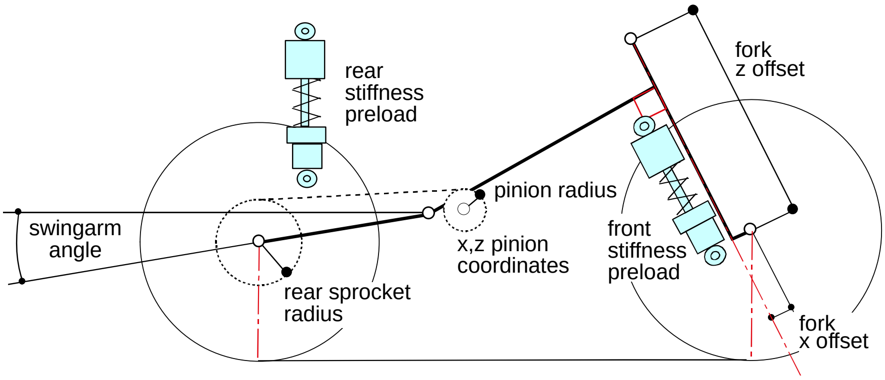

Figure 8 : Optimization independent variables

suspension travel should be progressive, in order to sweep the all available stroke with no fluctuations and no end stroke contact.
In the **middle** phase the main target is the stability, in order to avoid fluctuations on camber angle and yaw angle.
The **exit** phase starts when the throttle is switched on again and finishes when it is in fully-open. In this phase load distribution on the rear tire should allow maximum acceleration without increasing the yaw angle and the pitch angle. In this sense the wheelbase and the squat angle are critical parameters.
Figure 7 shows the dependent parameters that may be varied depending on the characteristics of track. The variation of these parameters is obtained by varying the independent parameters illustrated in Figure 8.

Case 1: Optimization of the normal trail during a braking manoeuvre

The following table reports the optimization of the normal trail with the other dependent parameters maintained constant. In the considered braking manoeuvre the normal trail should be increased from initial value 0.0795 m to the target value 0.083m.
It is interesting to note how not only the front but also the rear suspension setting influences the normal trail variation.

Dependent parameters	Wheelbase [m]	Caster angle [rad]	Normal trail [m]	Squat angle [rad]
Static condition: V=0 m/s, long acc=0 m/s^2, lat acc=0 m/s^2	1.4101	0.4425	0.0893	0.3195
Optimization condition: V=60 m/s, long acc= -8m/s^2, lat acc=0 m/s^2	1.3954	0.4082	0.0795	0.3325
Target values			0.083	
Optimized values				
Independent parameters	Front suspension preload (<0) [N]		Rear suspension preload (<0) [N]	
Reference values	-160		-997	
Optimized values	-435		-822	

Case 2: Optimization of the ormal trail and caster angle in static condition

In the second example both the caster angle and the normal trail are optimized with respect to the static condition. In this case the offset coordinates are varied in order to obtain the propose target values.

Dependent parameters	Wheelbase [m]	Caster angle [rad]	Normal trail [m]	Squat angle [rad]
Optimization condition: V=0 m/s, long acc=0 m/s^2, lat acc=0 m/s^2	1.4101	0.4425	0.0893	0.3195
Target values		0.42	0.080	
Optimized values		0.4194	0.0801	
Independent parameters	Offset z of the front fork [m]		Offset x of the front fork [m]	
Reference values	0.504		0.0340	
Optimized values	0.4723		0.0371	

Case 3: Optimization of the squat angle during acceleration in exiting from a curve

The third example shows the optimization of the squat angle during the exiting from a curve. The independent variables considered are the coordinates of the pinion respect the swingarm pivot.

Dependent parameters	Wheelbase [m]	Caster angle [rad]	Normal trail [m]	Squat angle [rad]
Optimization condition: V=30 m/s, long acc=5 m/s^2, lat acc=6 m/s^2	1.4221	0.4657	0.0982	0.2884
Target values				0.35
Optimized values				0.3505
Independent parameters	X pinion coordinate		Z pinion coordinate	
Reference values	0.084		0.0	
Optimized values	0.0656		0.0069	

Case 4: Optimization of the front suspension during braking manoeuvre

During a severe braking manoeuvre the optimal target is to sweep the available front suspension stroke without pad touching. The optimization was performed changing both the stiffness and the preload of the front suspension.

Dependent parameters	Front suspension travel (<0) [m]	Rear suspension travel (<0) [m]
Optimization condition: V=50 m/s, long acc= -8 m/s^2, lat acc=0 m/s^2	-0.0889	-0.0026
Target values	-0.11	
Optimized values	-0.11	
Independent parameters	Front suspension preload (<0) [N]	Front suspension stiffness [N/m]
Reference values	-160	20000
Optimized values	0	17500

CONCLUSION

A multibody software for dynamic analysis of two wheeled vehicles named FastBike Race has been introduced. This software integrates a multibody model of the motorcycle that allows to perform different kind of investigations like steady state analysis and frequency domain analysis. Steady state analysis deals with the calculation of the vehicle trim in static condition, in straight running, in steady state cornering and in braking/acceleration conditions. Frequency domain analysis module, with includes stability analysis, free-modes calculation and frequency response function evaluation, has been illustrated and commented by an example of chatter phenomena.
The distinctive feature of FastBike Race is the optimizer, that makes it possible to define the optimal suspension setup and the optimal geometry layout almost on the pit lane.

REFERENCES

(1) Cossalter, V. and Lot, R. (2002), "A Motorcycle Multi-Body Model for Real Time Simulations Based on the Natural Coordinates Approach", Vehicle System Dynamics Vol 37, pp. 423-448.
(2) Cossalter, V., Lot, R. and Maggio, F. (2003), "A Multibody Code for Motorcycle Handling and Stability Analysis with Validation and Examples of Application". SAE Paper 2003-32-0035.
(3) Cossalter, V.; Lot, R.; Massaro, M. (2007) "The influence of Frame Compliance and Rider Mobility on the Scooter Stability", Vehicle System Dynamics, in printing
(4) Lot R. and Da Lio M.: (2004) "A Symbolic Approach for Automatic Generation of The Equations of Motion of Multibody Systems, Multibody System Dynamics", Vol xx, ISSN 1384-564
(5) Cossalter, V., Lot, R., Maso, M., Massaro M., Sartori R. (2008) "A Motorcycle Riding Simulator for the Improvement of the Rider Safety", Fisita 2008, Munchen.
(6) Pacejka H. B. and Sharp, R S., 20 (1991), "Shear Force Development by Pneumatic Tyres in Steady State Conditions: A Review of Modelling Aspects", Vehicle System Dynamics pp.121-176.
(7) Riedel, A., (1996) "Standard Tire Interface", TYDEX Working Group, December
(8) Lot, R., (2004), "A Motorcycle Tire Model for Dynamic Simulations: Theoretical and Experimental Aspects", Meccanica Vol 39, pp 204-218 ISSN 0025-6455
(9) Y.TEZUKA, S.KOKUBU, Y.SHIOMI and S.KIYOTA (Honda R&D), "Vibration Characteristics Analysis in Vehicle Body Vertical Plane of Motorcycle during Turning", JSAE Paper Number: 20045022, 2004 JSAE Annual Congress, Yokohama, Japan, May 19 - 21, 2004
(10) V. Cossalter, R. Lot, M. Massaro, The Chatter of Racing Motorcycles, Vehicle System Dynamics: , Vol. 46, No. 4, April 2008, pp. 339–353