A Multibody Code for Motorcycle Handling and Stability Analysis with Validation and Examples of Application

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A Multibody Code for Motorcycle Handling and Stability Analysis with Validation and Examples of Application

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ABSTRACT

This work presents a new multibody software designed for investigating two wheeled vehicles dynamics. This code, named *FastBike,* can perform time steady state analyses, time domain simulations and frequency domain analyses. The steady state analysis allows for the calculation of the vehicle trim in static condition, in straight running and in steady cornering, both at constant speed and in braking/accelerating phase. Time domain analysis is of use for simulating typical maneuvers such as lane change, slalom, entering in a curve, path following and free control simulations. Moreover, these maneuvers can be reproduced in braking or accelerating conditions. Frequency domain analysis tool includes stability analysis and free-modes calculations, frequency response function evaluations and rider emulator design. Furthermore, results of the experimental validation of *FastBike*, which were carried out on a sports motorcycle, are summarized.

INTRODUCTION

Nowadays virtual prototyping and computer simulation tools are frequently used in motorcycle engineering for reducing the designing time, developing costs and for avoiding the risks associated with the tests. Mainly, a model of the vehicle is built up using a commercial multibody software. These codes make it possible to develop a customized model in a reasonable amount of time. Afterward, dynamic simulations can be performed and visualized. However, there are some critical aspects both in the phase of modeling and running simulations. In the modeling phase, the detail level of the vehicle description (i.e. the number of bodies, degrees of freedom and other features) must be chosen carefully. An approximate description of the vehicle may be inadequate for the subsequent dynamic analysis, whereas a too detailed model leads to difficulties in measuring or estimating the correct values of the necessary parameters. Moreover, the proper modeling of some elements, such as tires and shock absorbers, is very complex. The final validation of the model can be achieved only through tests on instrumented prototypes. In order to perform the simulations of typical maneuvers, the vehicle model has to be provided with an efficient virtual rider. The design of a control system that was simultaneously quick and stable is another difficulty. Many commercial multibody softwares are very powerful in making time simulations, but they are not suitable for performing inverse dynamic analysis (i.e. trim calculation, or stability analysis). Moreover, they rarely include the tools for performing frequency analysis through the frequency response functions (FRFs).

For the reasons mentioned above, the several research activities about motorcycle dynamics which has been done in the last several years at the Department of Mechanical Engineering (DIM) of the University of Padova, Italy, include the development of a multibody model specific for motorcycle. This activity is a part of a larger project, which includes the development of computer tool for handling and stability analysis [1],[2], the designing and assembly of equipment for measuring motorcycle parameters [3],[4],[5],[6] and the execution of experimental tests both on track and on road [7],[8]. Since the software is specifically designed for motorcycles, the multibody model takes into account all the needed peculiarities without exceeding in complexity. Morevore, the availability of the equations in analytical form has made possible the development of the tool for carrying out, easily and quickly, the steady state analysis, the free modes calculation and the frequency response functions evaluation. Obviously, time domain simulations can be done and the maneuvers are full customizable by the user. Great attention has been focused on computational efficiency, making the software suitable for the motorcycle simulator actually in

development at DIM [9]. Another typical application of the code is the numerical optimization of some motorcycle parameters [10]. Of course, the experimental equipment are employed both for measuring vehicle characteristics before performing simulations and afterwards for checking results.
The result of all these efforts is *FastBike*, a software for dynamic analysis of motorcycles. It has been provided with a user-friendly interface for inputting the data and planning simulations. Due to its characteristics, the software could be profitable both for research purposes and for industrial design.

In the next sections, descriptions of the features of *FastBike* are given, including some examples and some experimental results regarding its validation. The convenience of using *FastBike* instead of other multibody software is discussed.

THE MOTORCYCLE MODEL

The motorcycle model consists of six bodies: the front and rear wheels, the rear assembly (including frame, engine and fuel tank), the front assembly (including steering column, handlebars and front fork), the swinging arm and the front unsprung mass (including fork and brake calipers). Particular attention was posed in modeling components such as tires and shock absorbers. In literature many tires model are available [11], but they were designed and developed mainly for cars and trucks. Tire models specific for motorcycle have been developed only in recent years [12], [1], [13]. The tire model included in *FastBike* takes into account the geometry and the deformability of the carcass. It has been designed for working properly up to very large camber angle, and for providing exactly the forces/torques both in stationary and transient conditions. The front suspension is telescopic whereas the rear suspension is a swinging arm type. Shock absorbers were modeled using non-linear relations between force and suspension travel rate. However, the development of a more accurate model based upon neural network is in progress [14], [15].

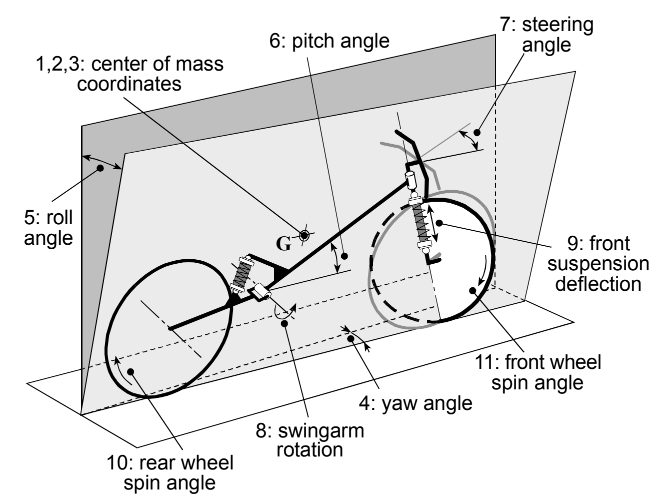

Fig. 1 eleven degrees of freedom motorcycle model

The chain power transmission is also modeled in detail. Aerodynamic effects are of course included. More details can be found on reference [2], [16].

As shown in Fig. 1, the vehicle has eleven degrees of freedom corresponding to the coordinates of the chassis center of mass, the pitch, roll, yaw and steering angles, the travel of front and rear suspensions and the wheel spin rotations. The virtual rider can control the vehicle by means of the handlebar, the brakes and the accelerator. The rider's movement away from the saddle and the corresponding control actions are not yet included in the model. Therefore the motorcycle has four inputs: the steering torque, the front and rear brake torques and the engine torque.

The equations of the motion were derived symbolically using Maple and subsequently implemented into a Fortran program. This approach has mainly two disadvantages: it is time consuming in the development phase and further updating is onerous. However, the advantages are considerable. The analytical approach allows the complete control of the mathematical model. Therefore, the equations can be optimized for maximizing the computational efficiency in time domain integration and can be re-arranged for carrying out other type of analyses. Some general-purpose multibody software contain the tools for performing the same analyses of *Fastbike*, but they often require the interaction with an external signal processing software. *Fastbike* works alone, results are found quickly and so it is suitable for parametric analyses. The functions included in *Fastbike* are explained in detail in the following sections.

The Fig. 2 shows a window of the input interface, which has been designed for managing vehicle characteristics and planning simulations.

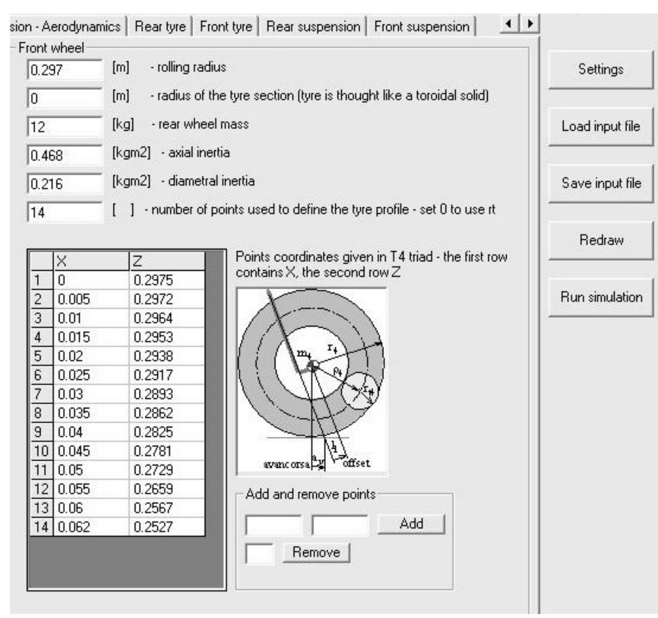

Fig. 2 example of FastBike graphics interface

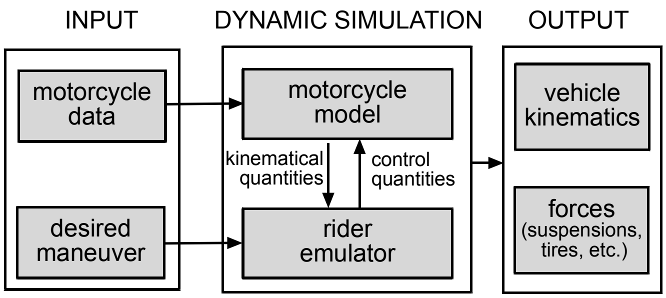

Fig. 3 structure of the subprogram for time domain analysis

TIME DOMAIN ANALYSIS

Time simulations are the most popular technique for evaluating the dynamic behavior of a vehicle. Analyses are carried out either by simulating the open-loop vehicle response to typical inputs or by establishing a driver model and simulating a closed loop pilot-vehicle system performance. The simplest case is the simulation of lane-change maneuvers for cars and trucks. Because of the capsize mode [17], motorcycles are intrinsically unstable and therefore it is nearly always necessary to include a control system for stabilizing the vehicle. The rider emulator included in *FastBike* is a non-linear PID control, which is composed of two sections. The first one controls the vehicle speed by means of the engine propulsive torque as well as the front and rear breaking torques. The second section controls the steering torque and is responsible for the lateral stability and trajectory following. The structure of *FastBike* subprogram for time domain analysis is summarized in Fig. 3.

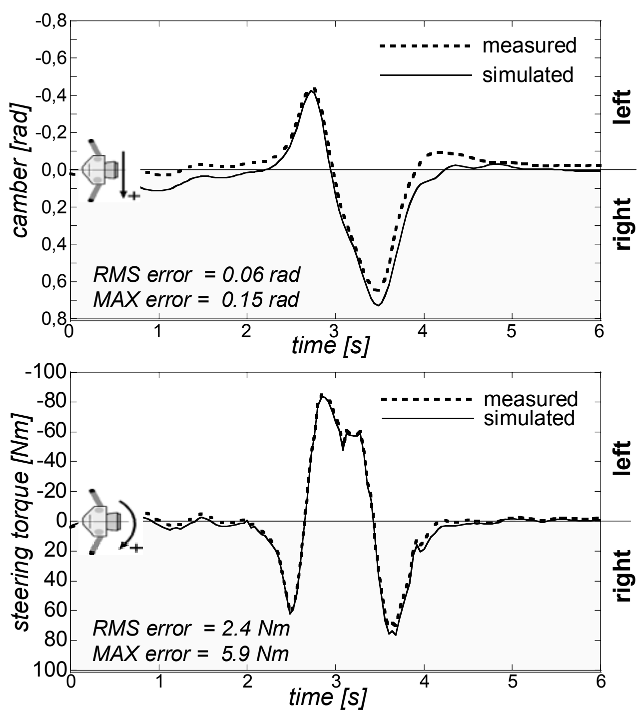

Fig. 4 camber angle and steering torque during a lane change maneuver

Desired maneuvers can be planned in the appropriate window of the input interface, by choosing one of the pre-defined parametric maneuvers. The library includes straight running, lane change, slalom, obstacle avoidance, entering in a curve and others. All maneuvers can be planned at constant or variable speed reproducing braking and accelerating transient states. Alternatively, by supplying the program with an appropriately formatted file, the simulation of a generic maneuver can be carried out. In the same manner, maneuvers that were previously recorded on a track or on road, can be reproduced.

As an example, the Fig. 4 shows the roll angle and the steering torque during a lane change maneuver having a width of 3.6 m and a length of about 40 m. The maneuver was carried out with a sport motorcycle at a speed of about 25 m/s. The agreement between simulations and experimental data is excellent, proving the suitability of the model. Indeed, the overall error (RMS) of steering torque is less than 3% of its peak value and the overall error of the roll angle is about 9% of its peak value. For more details about these tests, see references [2] and [7].

STEADY STATE ANALYSIS

The purpose of steady state analysis is to determine the trim of the motorcycle. Usually, multibody software calculates the steady state by integrating equations of motion in the time domain until the desired configuration is reached. Following this approach, a suitable control system is necessary for moving the vehicle from the initial configuration to the final desired state. Moreover, the simulation must be long enough to extinguish transient motions. *FastBike* uses the inverse dynamic approach, and both the previous problems are avoided. The steady state conditions are superimposed to the vehicle and the trim is calculated by solving the corresponding non-linear algebraic equations [1], [18]. This method makes it possible to calculate the vehicle trim in static condition, in straight running and in steady cornering, as well as in braking or accelerating conditions. No control system is needed and so the calculation becomes very fast.

As an example, Fig. 5 shows the contour plot of the steering torque in steady turning conditions as a function of the cornering curvature and the forward speed; the vehicle is a powerful sports motorcycle. It should be observed that the maximum speed that can be kept in cornering depends on both the cornering radius and the tire performances. For any fixed turning radius, the figure shows that as the velocity increases, the steering torque decreases until a minimum, then it increases and it can reach positive values when the speed is high. In the whole range of speed and curvature, steering torque is low in magnitude and mostly negative (i.e. opposite to the yaw speed). It has been observed [1], [7], [18] that these conditions indicates good vehicle handling characteristics. Fig. 5 also contains the results of some experimental tests, which are represented by means of

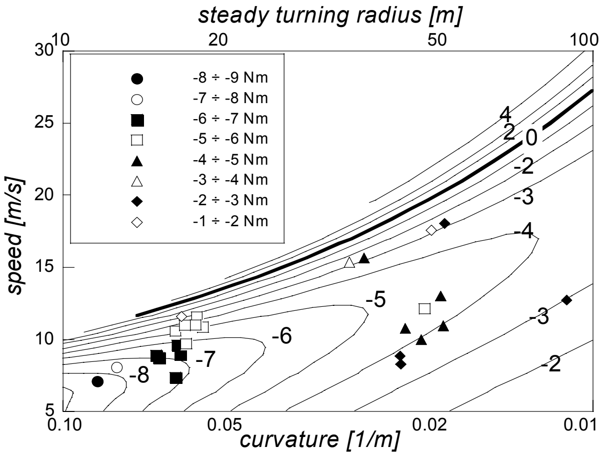

Fig. 5 steering torque in steady state cornering

discrete markets. These measurements were particularly difficult [7]. In fact, each correcting action provided by the rider introduces an undesired variability on the steering value. Moreover, the steering torque in steady conditions is a small fraction of the torque transducer range. The figure shows a good agreement between simulated and experimental data.

It is worth to point out that *FastBike* had carried out the several hundred simulations necessary for drawing Fig. 5 in few seconds. Other multibody software would had required a much greater amount of time. This feature makes *FastBike* suitable for parametric analysis and for optimization processes as well [10].

MODAL ANALYSIS

The modal and stability analysis of the motorcycle gives important information about rider safety, handling capabilities [19] and rider comfort [20]. Indeed, these topics have received the attention of many researchers in the last thirty years (a detailed bibliography can be found in [19]). The calculation of free modes in straight running at constant speed is a relatively simple task, as testified by a large amount of published works [17], [19], [21], [22]. On the contrary, the calculation of the free modes in steady cornering is a complex task and very few works are available on this topic [23], [24], [25]. In *FastBike,* the theoretical difficulties of calculating free modes in steady cornering were solved by linearizing the equation of motions with respect to a moving frame [25]. In this way it is also possible to calculate modes in braking or accelerating maneuvers.

As an example, Fig. 6 shows the complex eigenvalues calculated for straight motion at constant speed, considering speed values from 5 m/s to 70 m/s. The plot is split into two areas: the white one corresponds to stable modes (the damping ratio is represented by means of dotted lines), whereas the gray area corresponds to unstable modes. The free-modes of the motorcycle can be grouped as *in-plane* modes and *out-of-plane* modes. The *in-plane* modes involve the motion of the motorcycle in its symmetrical plane. In the plot,

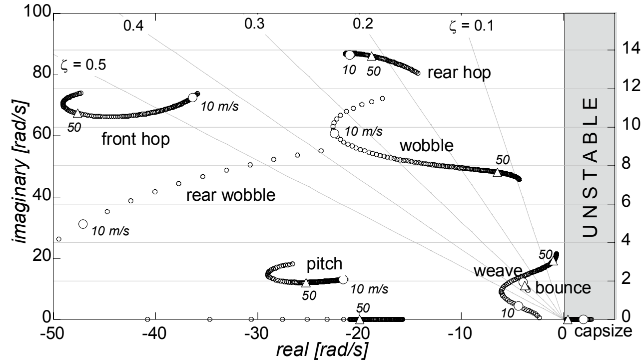

Fig. 6 Motorcycle free modes in straight running

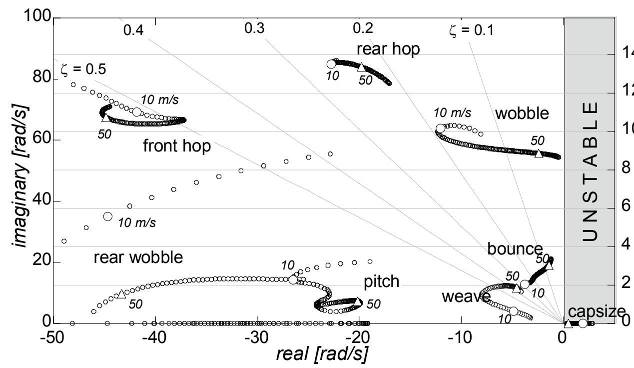

Fig. 7 Motorcycle free modes in steady cornering

they are labeled as pitch, bounce, front and rear wheel hops, in accordance with the existing literature on the topic. The *out-of-plane* modes involve the lateral motion of the vehicle. They are labeled as capsize, weave, wobble and rear wobble mode.

The Fig. 7 shows the complex eigenvalues in steady cornering for a fixed lateral acceleration of 5 m/s^2. The main effect of the camber angle is the coupling between *in-plane* and *out-of-plane* modes. For more details see reference [25].

Some experimental tests were done for validating numerical results. Several practical difficulties were found in exciting the motorcycle modes. Tests were carried out by running with a small camber angle over a

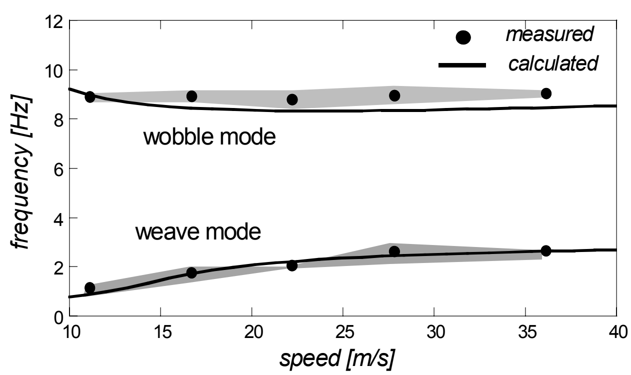

Fig. 8 – Comparison between calculated and measured frequencies of weave and wobble modes in straight running

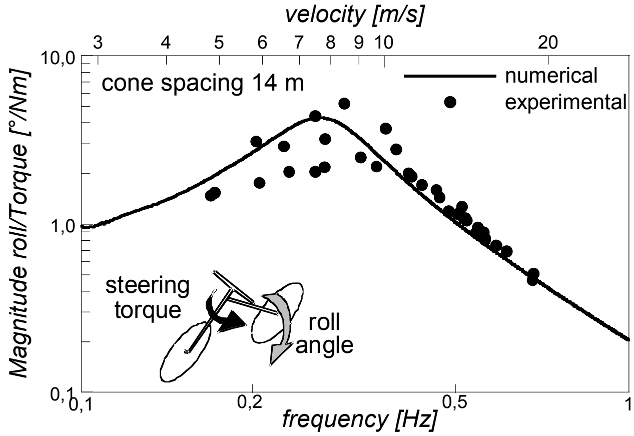

Fig. 9 Frequency Response Function between roll angle and steering torque

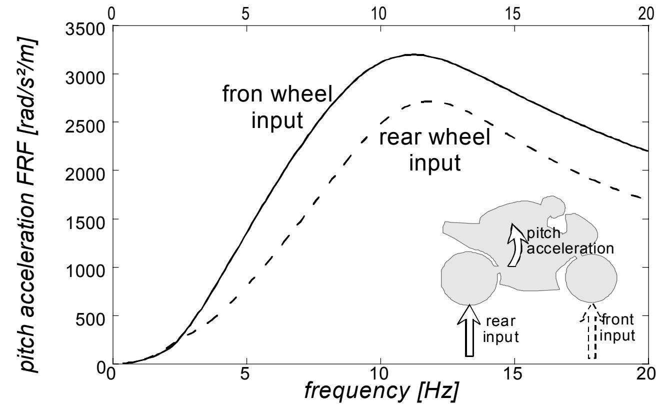

Fig. 10 Frequency response function between pitch acceleration and of road irregularities

series of bumps spaced at different distances. In this way, the front frame was exposed to a succession of impulses and it was excited in a frequency range from about 1 to 12 Hz [25]. Results are included in Fig. 8, which shows the frequencies of weave and wobble modes. A good agreement between experiment and simulation can be observed.

FREQUENCY RESPONSE FUNCTIONS

Frequency response functions (FRFs) are useful in studying motorcycle behavior both for handling and comfort analysis. Indeed, a way of analyzing the handling characteristics of a motorcycle is studying how the vehicle motion is produced by the rider input. These input-output relations may be effectively expressed using the frequency response function representation, for example between the roll angle and the steering torque [8]. Moreover, the FRFs between frame accelerations and road irregularities are a useful instruments for evaluating the ride comfort [26].

FastBike calculates FRFs through the numerical linearization of the equations of motion. Once again, the use of non-inertial coordinates in the linearization process makes it possible to calculate FRFs not only in straight running at constant speed, but also in steady cornering or in braking/accelerating conditions. General-purpose multibody software do not usually perform this kind of analysis. Two example are presented below.

Fig. 9 shows the magnitude of the FRF between the camber angle and the steering torque in a slalom test. The cone spacing is kept constant and the maneuver is carried out at several speeds. The circular markets represent the experimental data whereas the solid line corresponds to the FRF calculated with *FastBike* [8]. A good matching between experimental data and numerical calculation is evident. Analyzing the figure, it can be observed that by increasing speed from very low values, the ratio between camber angle and steering torque increases since it reaches a peak at the speed of about 7-8 m/s. Over this critical value, the magnitude quickly decreases as the speed increases. The condition of peak roll-to-torque ratio means that less torque is required for the same maneuver, i.e. the vehicle should be easier to ride. This was confirmed by the impressions of riders, which gave a rating of “better handling” near this speed. Fig. 9. shows also the FRF calculated using FastBike [8].

Fig. 10 shows the FRF between the pitch acceleration of the chassis and the vertical displacement of the front and rear wheel contact points which is due to road irregularities. The pitch acceleration increases as the excitation frequency increases, since the acceleration reaches a maximum for a frequency of about 12 Hz for the rear wheel input and about 11 Hz for the front wheel input. These peaks corresponds the natural frequency of the rear and front hops, which can also be seen in Fig. 6.

Because the ride comfort decreases as the acceleration level increases, the FRF between chassis accelerations and road represents the starting point for its evaluation. The acceleration level depends not only upon the frequency, but also upon the vehicle speed [20]. However, by properly combining vehicle FRF, vehicle speed and road characteristics, a mean value of the induced acceleration can be evaluated [26].

CONCLUSIONS

FastBike, a new multibody software for dynamic analysis of two wheeled vehicles, which was entirely developed at the Department of Mechanical Engineering of the University of Padova, is presented. A description of the motorcycle model is given and its accuracy is demonstrated through several experimental tests. The capabilities of the software are illustrated, and some typical applications are included.

The model of the motorcycle consists of six rigid bodies and has eleven degrees of freedom. This representation of the vehicle is adequate for reproducing dynamic phenomena up to about 15-20 Hz. The good match between Fastbike calculations and experimental data confirms it. The comparisons included in the paper regard several typical maneuvers (steady cornering, lane change and slalom) and weave - wobble frequency investigation. Primarily, the capabilities of *FastBike* are steady state analysis, time domain simulations and frequency domain analysis. Steady state analysis makes it possible to calculate the vehicle trim in static condition, in straight running, in steady cornering and in braking/accelerating conditions. Time domain simulations can be performed for investigating typical maneuvers such as lane change, slalom, braking in straight running or in curve, path following and free control responses. Frequency domain analysis tools are designed for stability analysis, calculating the free-modes, identifying the frequency response functions (FRFs) and developing a rider emulator. Several of these features are not commonly available in other commercial multibody software. Therefore, *FastBike* represents an innovative and useful tool for virtual prototyping of motorcycle.

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