EXPLORATORY STUDY OF THE DYNAMIC BEHAVIOUR OF MOTORCYCLE-RIDER DURING INCIPIENT FALL EVENTS

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ABSTRACT

The continuing study of motorcycle riding gear carried out by Dainese has led to the development of a system of protective riding gear with an integrated air-bag. The aim of this system is not only to reduce the injuries to a rider due to impacts with opposing objects but also to prevent direct contact with the terrain caused by accidental falls.

The scope of this research was to use a multi-body code to simulate the fall of the motorcycle-rider system to determine which parameters can be useful in identifying the early stage of fall. Determining such parameters will be used to develop a logic of control able to activate a passive system of protection, a type of air-bag, included both on the motorcycle and in the rider's protective gear. The rider model was based on a crash test dummy scheme. Dynamic behavior of the system was analyzed in diverse critical conditions. As a result useful information regarding possible crash events was collected.

INTRODUCTION

The urge for safety in the automotive field is growing every year, but besides the great efforts put forth in research, there is still much to do. Until significant changes are implemented in road architecture, new strategies will need to be identified for reducing crash related injuries. This is particularly true in the motorcycle field. While in the automotive sector research and regulation had begun to chase safety far in the past, with regard to motorcycles the situation is still in its infancy. Motorcycle safety relies mostly on passive systems. As such, significant safety goals have been achieved in recent years through improvents in riding gear. However there is still much work to do for catching up with the safety levels achieved by cars. With regard to active safety, the principal improvement has been the recent introduction of ABS to various motorcycle models.
From the safety regulation point of view, the situation is still unchanged, and effectively we can say that, in most countries, roads are predominantly made for cars: any other type of vehicle is seen as just a novelty or as something bizarre and unusual. Directly related to this issue many believe that riding motorcycles is excessively hazardous, however this idea can be effectively modified if advances in safety show relevant improvement. Dealing with the motorcycle's related intricacies has always proven complex due to the additional degrees of freedom associated with the vehicle [1]. However this added freedom could offer new possibilities to the crash safety challenge, giving space for new solutions different from those used in the car industry. Two of the more interesting enhancements in passive safety are coming from the air-bag field; both air-bags equipped on vehicles and on riders are being taking into production phase. Currently the two systems are not conceived to work together, but, since they aim to fulfill different targets, this handicap at this stage is acceptable. Vehicle installed air-bags aim to protect the rider in vehicle versus vehicle impact, while rider installed air-bags aim to avoid injury from bodily impact with terrain during single vehicle accidents. As always when dealing with air-bag related problems, one of the biggest challenges is developing the activation algorithm. For vehicle versus vehicle, and vehicle versus object impact, the strategy is already established from the car industry and needs only to be applied appropriately. However with regard to motorcycle single vehicle, loss of control accidents, such a strategy has yet to be conceived. Preliminary steps in defining such a strategy will be the aim of this article.

MODEL OF THE RIDER

Wanting to investigate the dynamics of the fall in the early stage, we shall consider that the rider is not yet in contact with the road surface. Although some account of the impact aspects of a collision [6] is included, we focused on a multi-body model for dynamic analysis of the motorcycle-rider system. For succeeding in such a task, a rather complex model of the rider was developed. It consists in a total of 13 main and 25 contact bodies, connected together by means of 22 kinematic joints.

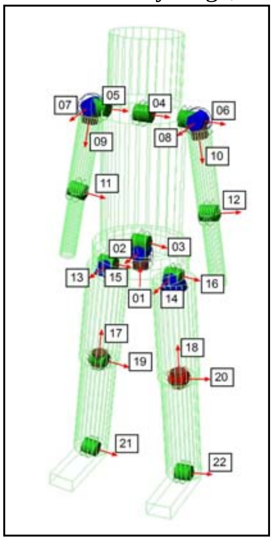

Figure 1. Stand alone model of the rider

Using this new rider model in conjunction with an proven multi-body model for motorcycle dynamic analysis, we obtained the starting virtual environment for realizing the various simulations.

Model enhanced features

One of the most difficult tasks met during the realization of the rider model was defining the various body parts and joints in a realistic way. There were several main problems: first, the position to assign to the rider; then, what type of constraints were appropriate for describing the actual rider movement during falls, finally the stiffness and damping to assign to each joint. To find a solution to the problem, we started from the human 50th percentile data and from a rider model developed at the University of Tokyo [3]. We changed many factors to accommodate the new features of our model: we added several d.o.f. and also changed the description of the joints. Another problem needed to be solved, how to link the rider to the vehicle without preventing the freedom of movement needed for this particular simulation. For this purpose, many strategies were tried using different types of time-limited kinematic links, but finally the solution was found using a different approach based on a modified hertzian contact between bodies. We added to the model several contact bodies with the purpose of simulating realistic contact between the rider and the vehicle. These contact bodies also aimed to simulate the typical points of contact between riding protective gear and surroundings. The contact approach had the disadvantage of slowing down the simulations but fulfilled the other requirements. To realize the appropriate linking condition between the rider and the saddle, a torque exerted by the hip realized the contact between the knees and the fairing.
The ground was modelled as a plane body which generates contact upon penetration by imposing bodies. The tire forces were based on the Pacejka Magic Formula [5], specifically modified to represent motorcycle tires [4]. Care should be taken when viewing crash results since due to the large slip values involved in these type of maneuvers, the tire forces cannot always be considered reliable. Nevertheless we should note that the first instants from the start of the fall are the most important for deciding the subsequent dynamic behaviour of the motorcycle, and at this stage the tire forces are still reliable.
Another consideration that should be done is that the tire parameters change the behaviour of the motorcycle considerably, so a different set of tire parameters can led to different results.

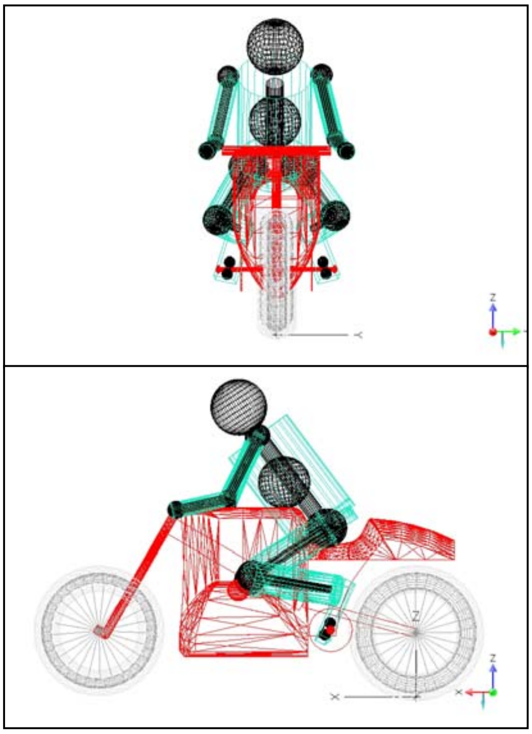

Figure 2. Assembled model with black indicating contact elements.

The Control System of the Model

The control system was based on a PD control algorithm, using the roll of the vehicle and the torque exerted through the motorcycle handlebar as working variables.
Basically, depending on the type of maneuver, a roll value is passed to the steer actuator which generates a torque proportional to the gap between the desired roll an the actual roll, with a damping term depending on the rolling speed of the motorcycle.

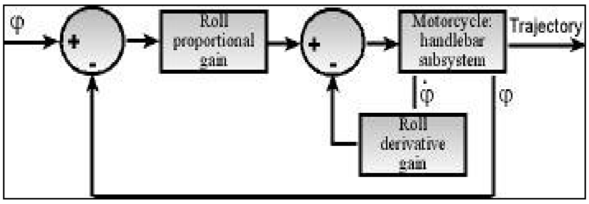

Figure 3. Control system of the virtual model.

This simple scheme can be justified in this context. At this early stage of exploration the goal was not to model the complex relationship between the rider control technique over the motorcycle, rather the focus was that of using the vehicle as a means, letting the rider movements evolve freely in the early stage of the fall. In general, the act of falling implies a loss of control, hence this simple control is sufficient to deliver the model to the desired state. In addition to the basic roll control other auxiliary control routines were introduced, determining factors such the forces exerted between the hands of the rider and the handlebars, and the torque exerted by the hips these subroutine were necessary to take into account the changing attitude of the rider with respect to the motorcycle control during the simulation. The developed model was used in a series of simulations of critical maneuvers. Three particular cases have been chosen: critical front braking, critical rear braking, and high-side fall.

ANALYSIS OF THE MANEUVERS

The dynamic analysis of a motorcycle is very complex due to its own instability, especially at low speed. Without the rider's control, a motorcycle can fall not only when the motorcycle is stopping but also when it is running in straight uniform motion [2]. We will now investigate the dynamics of the motorcycle when control limits are exceeded and falling is imminent. It is the intent of the following simulations to represent the initial stages of the fall as such the simulation halts when roll angle exceeds 1.3 rad (75 deg).

Case 1: Low-side Fall due to Front Braking

For the following description see Figure 4.
We will now consider a motorcycle during a critical braking condition, in which the rider engages the front brake during steady turning, causing the motorcycle to slide off the road. The scenario could be the one of a motorcycle entering in a curve with excessive speed and trying to avoid an unforeseen obstacle.
This type of fall is common among inexperienced drivers. Being unaccustomed to critical driving situations, they react instinctively to the unexpected condition, ignoring the limits of adherence of the tires. Sometimes however this type of fall also happens to experienced driver on unexpected, uneven terrain. In order to get a more clear comprehension of the maneuver the time evolution of the simulation parameters is presented in Figure 4.

Frame A - Shows the initial stage of the maneuver: the motorcycle is running in steady turning at the speed of 40 m/s, the camber angle is about 30°.
Frame B - At this stage the rider starts braking with the front brake only. Due to the braking longitudinal slip, the side force necessary for maintaining equilibrium is obtained with a slip angle greater than the one necessary in curve without the presence of the braking force.
Frame C - The tire reaches its own adherence limit proportional to the normal load, but because of the load transfer suffered by the bike during the braking maneuver, the augmented adherence permits to the rider to maintain control over the motorcycle.
In these conditions it is quite possible for the side force produced by the front wheel to be insufficient; consequently the front wheel increases its slip angle.
Frame D - The force is still not sufficient to maintain the trajectory so the slip angle continues to increase accordingly. In order to try to follow the desired trajectory, the driver is turning the handle-bar with increasing force, but at this point the steering head reach its rotational limit. The force is still not sufficient to maintain the trajectory so the slip angle continues to increase accordingly. Due to the maximum in the vertical force, the lateral force of the front tire also reaches its maximum. An important thing to note at this point is the rapid increase in the roll velocities, this should suggest that the rider is beginning to lose control of the vehicle and is not more able to maintain a determined inclination.
Frame E - With regard to the braking action, the driver can decide to stop or to continue acting on the front wheel in order to get more control of the motorcycle. If the braking action persists the front tire continues slipping to external side.
At this point the front wheel rotational speed is zero, so the front tire is completely sliding.
In the simulation braking continues. The front tire now is almost unloaded, primarily due to the roll angular momentum, as such the lateral force is largely insufficient.
Frame F - The motorcycle tilts and falls laterally. In the fall motion the vehicle also drags the driver down with a certain lag depending on the holding conditions. The simulation ends: fall is in act.
If the driver is well protected and other vehicles are not in a collision trajectory, the fall may not be dangerous, in the sense that the motorcycle does not fall against the driver. Eventually injuries could come from the bruising contact with asphalt and any incidental impact with objects surrounding the road.

Case 2: Low-side Fall due to Rear Braking

For the following description see Figure 5.
We will now consider a motorcycle braking the rear wheel while in a curve.
The rider maintains the rear braking action for the duration of the simulation. The scenario could be the one of a motorcycle entering in a curve with excessive speed and, trying to avoid entering the opposing lane, the rider applies the rear brake. The rear tire of the simulation encounters a low friction surface, such as dirt or gravel, and loses adherence. This type of fall is less common but also happens to expert drivers.

Frame A - Shows the initial stage of the maneuver: the motorcycle is running in steady turning at the speed of 40 m/s, the camber angle is about 30°.
Frame B - At this stage the rider starts braking with the rear brake only. Due to the braking longitudinal

slip, the side force, necessary for maintaining equilibrium, is obtained with a slip angle greater than the one necessary in curve without the presence of the braking force, consequently the rear wheel increases its slip.

Frame C - The tire reaches its own adherence limit proportional to the normal load. In these conditions it is quite possible for the side force produced by the rear wheel to be insufficient; consequently the rear wheel continue to increases its slip angle. The rider, trying to control the vehicle, rapidly increases the steer angle. Consequently the front slip angle increases.

Frame D - The spin motion of the rear wheel halts, the rear tire now is longitudinally sliding with a speed equal to that of the vehicle.

Frame E - The steer angle reaches the maximum possible. From this point forward the rider is no longer able to maintain a steering control on the motorcycle.

Frame F - Due to the load transfer, the rear tire is now completely unloaded so the possibility of exerting a lateral force no longer exists.

Frame G - Due to the yaw motion the front tire is almost orthogonal to the trajectory. So slip parameters lose sense, the tire behavior in this zone is totally unpredictable.

Frame H - The motorcycle tilts and falls laterally. In the fall motion the vehicle also drags the driver down. The simulation ends.

The closing comments made for “Case 1” apply also in this case.

Case 3: High-side Fall

For the following description see Figure 6.

We will now consider a motorcycle suddenly accelerating during a curve.

The scenario is one of the most common encountered during competition.

The typical occasion when this happens, is when the rider attempts to exit from a curve with maximum velocity. He anticipates more traction than is available, and opens the gas while the motorcycle is still leaned significantly.

Frame A - Shows the initial stage of the maneuver: the motorcycle is running in steady turning at the speed of 40 m/s, the camber angle is about 30°. The rider instantly opens the throttle; the rear tire starts to increase greatly its longitudinal slip while the rear wheel is spinning. The front wheel is also increasing its slip angle because load transfer has already unloaded the front wheel.

Frame B - The rider stops accelerating and releases the throttle. A small quantity of braking torque is present due to the engine braking. The front tire stops increasing its slip angle while that of the rear tire continues to increase. The large side slip, which is still present, generates a lateral force impulse that is not balanced. The result is that the motorcycle is violently twisted and pushed upwards.

Frame C - The rear tire longitudinal slip goes to zero, hence, as the lateral slip angle grows the lateral force can fully develop as permitted by the Magic Formula. The high-side is in act. The time delay between the two maximums in the slip happen because the longitudinal slip has to decrease below a certain amount to permit the lateral force to grow and to stop the sliding of the tire.

Frame D - The vertical force goes to zero, and the tire loses contact. The steer angle reaches its limit, but the vehicle is still controllable.

Frame E - The handlebar again reaches its limit, the lateral force is now positive to compensate for the steering angle. The motorcycle is weaving about the roll and yaw axes.

Frame F - Another plateau appears in the vertical force, rapidly followed by a new maximum. The motorcycle is oscillating vertically, actuating the rear shock. After having absorbed part of the lateral force caused by the high side, the compression of the spring is released, projecting the rider upwards.

Frame G - The rider is now almost totally separated from the motorcycle, and is ejected skyward.

Frame H - The simulation ends. The vehicle is almost completely tilted and the rider is jettisoned from the motorcycle. In this particular simulation the roll velocity of the rider and that of the vehicle are opposite.

With particular attention to Figure 7, we can describe the initial phases of the high-side. From A to B we see the response to the instantaneous acceleration. The tire reaches the boundary of the traction ellipse, this represents the saturation limit of the forces. Moving toward condition B, as the slip continues to increase, first the force reaches its saturation limit and immediately after starts to decrease (Pacejka model). From here over, the high slip produced in the thrusting phase starts to generate an impulsive lateral force, which reaches the maximum at C. The lateral force generated in this manner is mostly unbalanced, so the vehicle starts tilting in the opposite direction. If the lateral impulse is high enough, the motorcycle falls immediately; if it is not the vehicle starts weaving and depending on the ability of the rider, control over the vehicle can be regained, otherwise a fall is imminent.

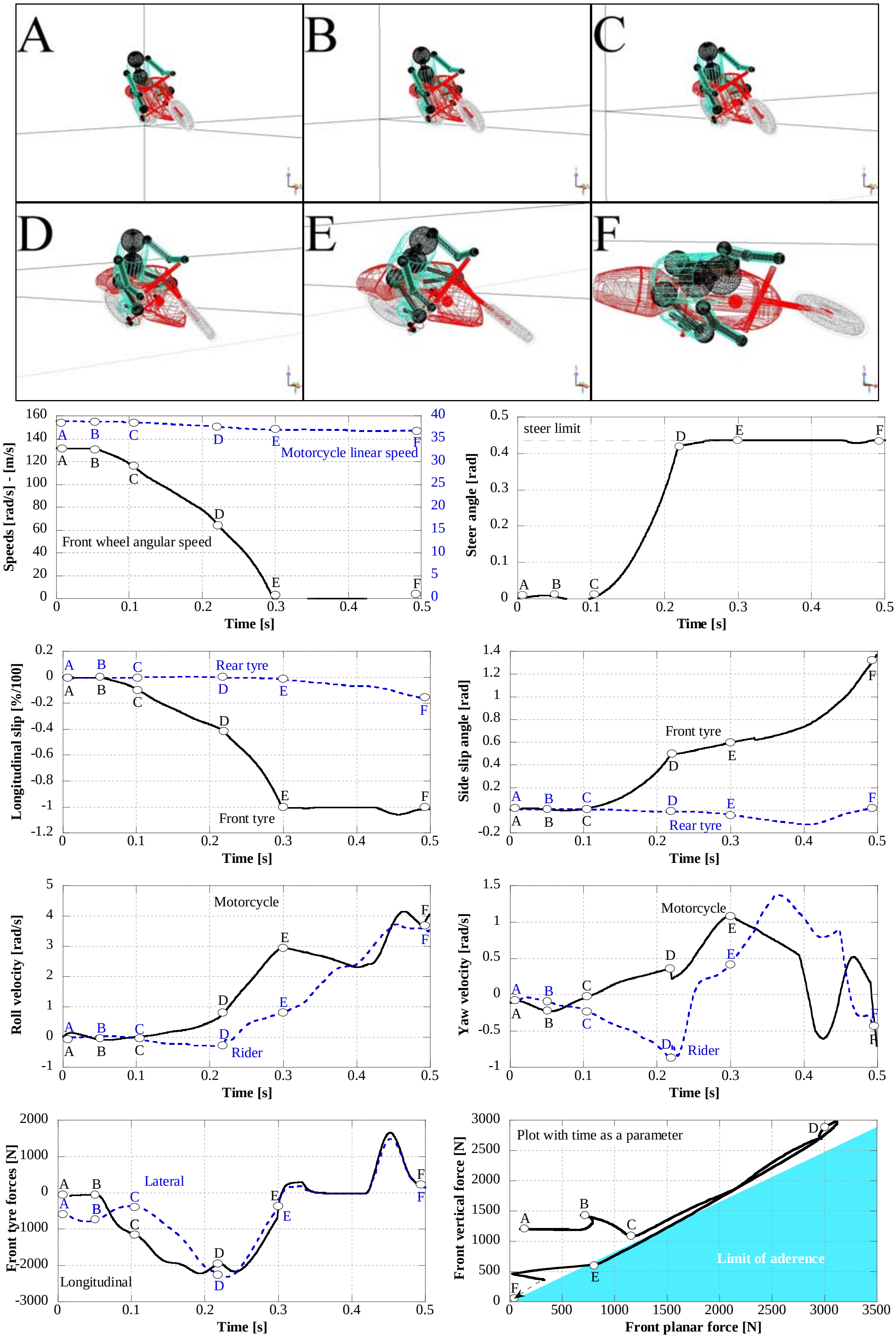

Figure 4. (Case 1) Top, six views of the simulated environment; Bottom, plots of different simulated quantities: motorcycle speed and front wheel speed, steer angle, longitudinal slip, slip angle, roll velocity, yaw velocity, tire forces.

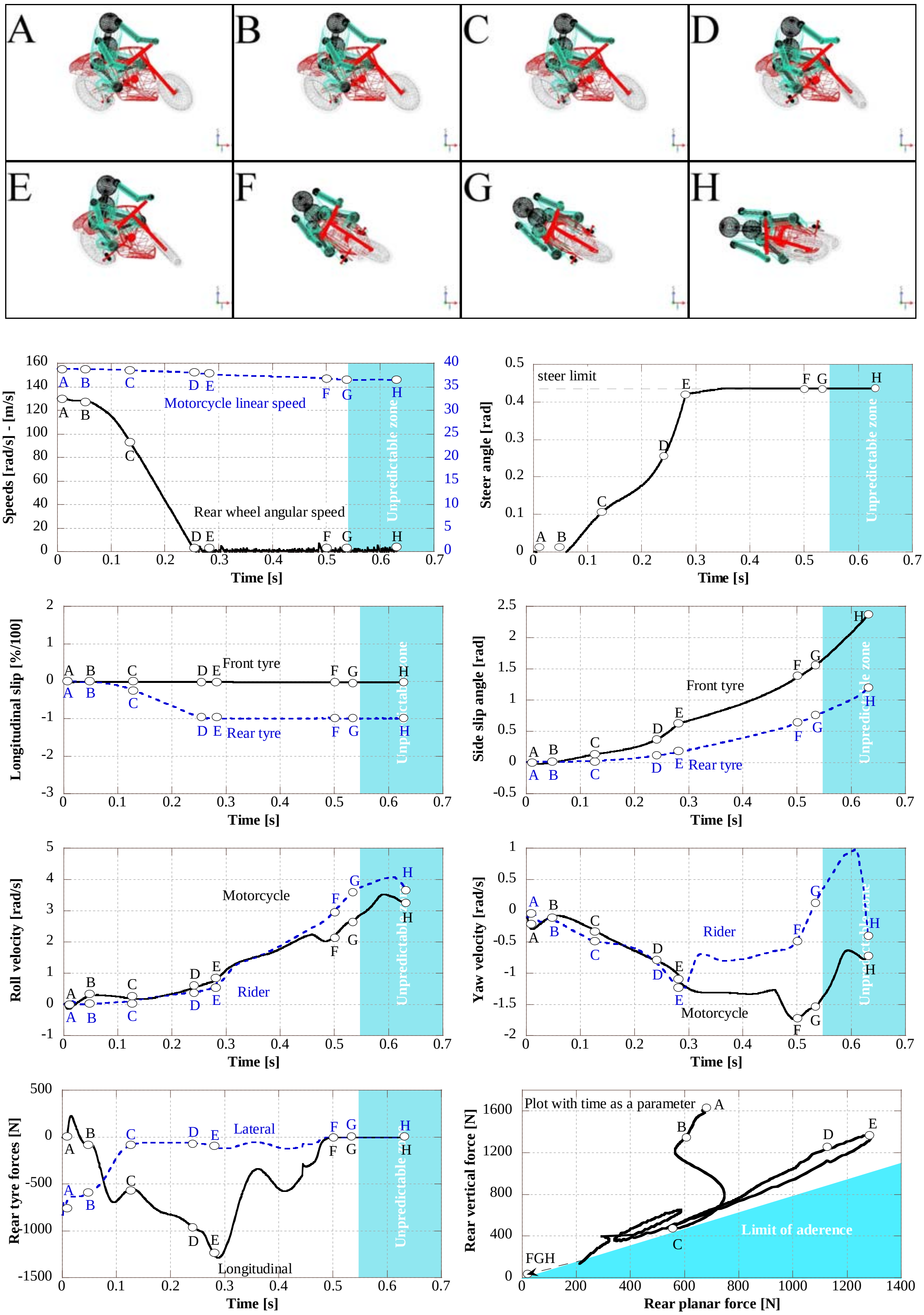

Figure 5. (Case 2) Top, eight views of the simulated environment; Bottom, plots of different simulated quantities: motorcycle speed and front wheel speed, steer angle, longitudinal slip, slip angle, roll velocity, yaw velocity, tire forces.

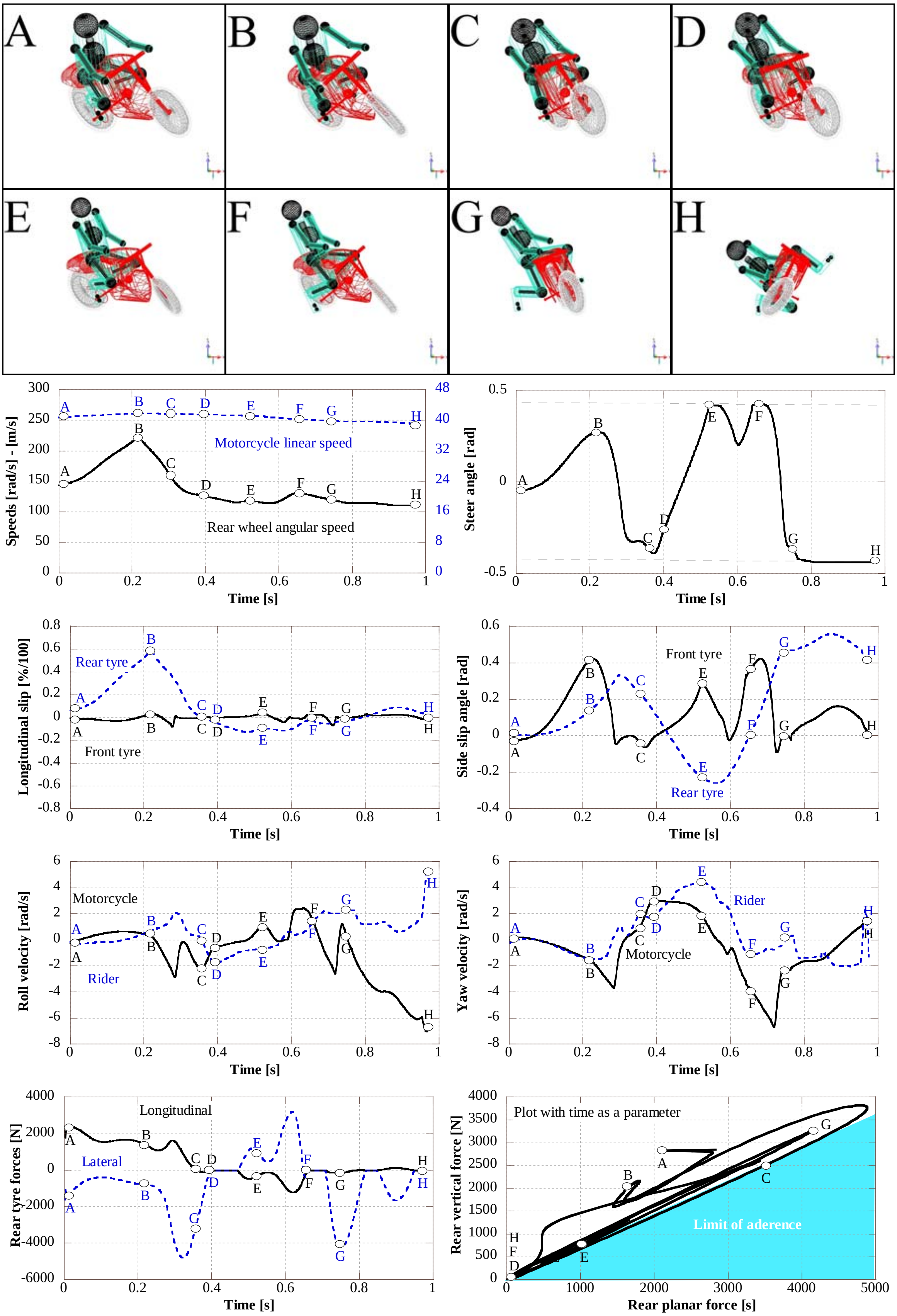

Figure 6. (Case 3) Top, eight views of the simulated environment; Bottom, plots of different simulated quantities: motorcycle speed and front wheel speed, steer angle, longitudinal slip, slip angle, roll velocity, yaw velocity, tire forces.

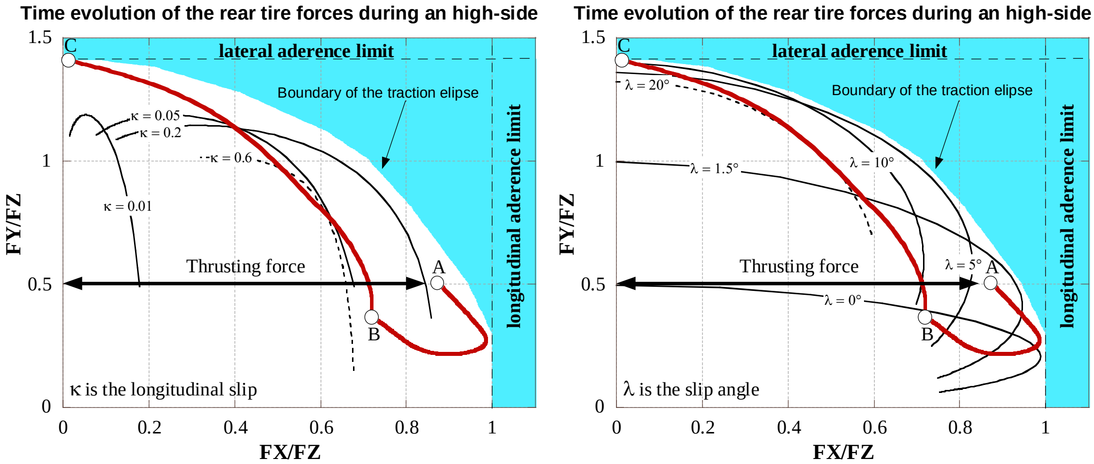

Figure 7. (Case 3) This graph show the time evolution of a high-side with reference to the traction elipse.

CONCLUSIONS

This exploratory study hoped to improve our knowledge of dynamic behavior of motorcycle-rider system during critical conditions, and to further identify some parameters which could be used to improve actual active and passive safety system. Although additional work will be needed to solidify this cause, the current study is an attempt to mark the first steps in the right direction. Three simulation cases are summarized and a number of relevant parameters are shown. These parameters may prove useful in determining the control algorithm for a multi purposes air-bags deployment system.
The current study also shows that great advantages can be gained by using multi-body modeling to simulate complex dynamics systems. Although the computational burden of these simulations is still high, such tools can certainly be used to reduce, or at least give direction to, the number of expensive (and sometimes dangerous) experimental tests which must be carried out for fulfill the design process.

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