Non linear optimization of a sport motorcycle's suspension interconnection system

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***Abstract*—A high fidelity nonlinear model of a sport motorcycle is modified to include interconnected suspension forces between the front and rear ends. The comfort and the suspensions efficiency have been studied for a wide range of interconnection stiffness and damping coefficients. An optimization of these coefficients is performed considering different possible mechanical implementations, going from a simple damping connection to full variable stiffness and damping coefficients depending on the speed. Finally the system is analyzed from the stability point of view to ensure that the oscillating modes are not strongly modified and the system stability is not compromised.**

Keywords—motorcycle; dynamics; interconnected suspension; stability; VehicleSim

I. Introduction

Interconnected suspensions have been widely used on car industry. Nowadays most of the marketed cars are equipped with antiroll bars that connect mechanically the two wheels of the front and rear ends separately. Although the connection between the front and the rear ends is not as usual as the antiroll bars, some notable example has been marketed, being the 1948 Citroën 2CV the first mass production car fitting this system. Some carry on research on semi-active/passive connected suspension obtaining good results such as [1]. However, in the two wheels field, these systems are not extended although some proposal can be found. One of the most significant examples is that Creuat [2] has introduced in an electric motorcycle prototype. Also a couple of bicycles concept demonstrators have been developed by particulars ([3] and [4]).

Usually the interconnection is presented as a way to uncouple the pitch and bounce modes involved in the suspension motion. With an interconnected suspension system, their frequencies and damping can be set independently. In this work, we focus on the suspension performance and how interconnected suspensions can improve it. The final goal is to obtain the optimized interconnection parameters that achieve an improved performance of the entire suspension system.

Four response variables have been stated to be studied. Two of them related with the precision of the suspension and the other two with the rider's comfort. The two first are the front wheel and the rear wheel fly times after a bump. That means the time during each wheel looses contact with the road. The control that the rider has over the motorcycle is drastically reduced if one wheel is out of the ground, being the front wheel the most critical. Shorter fly times increase the control during road perturbations and represent a better suspension precision. These can be calculated by the time while the tyre contact forces are equal to zero.

On the other hand, the maximum pitch achieved by the motorcycle's main frame and the maximum acceleration perceived by the rider have been chosen as good indicators of the rider's comfort. Smaller values of these outputs for a bump input becomes in better comfort results.

By means of a non-linear high fidelity motorcycle model and dynamics simulations it can be predicted how various suspension settings will affect the performance of the vehicle. Carrying on different optimization processes, it can be finally proposed a suitable configuration of the interconnection system for different mechanical implementations. These theoretical mechanical implementations consider different complexity scenarios. The simplest interconnection mechanism proposed consists in a direct connection of the front fork to the rear swinging-arm through a damper unit with constant damping value. An increase in complexity results from the use of dampers with speed variable coefficients in order to achieve different damping values for the different forward speeds. Finally, the most complex configuration would imply the use of actuators to provide variable interconnection stiffness coefficients. In the light of the results, configurations for constant stiffness coefficient are not proposed due to the fact that while a positive value of the interconnection stiffness coefficient returns good results in terms of overall precision for speeds under 40m/s, this precision is worsened for speed over this point. However, the opposite happens with negative values of this coefficient as can be observed in Fig. 4.

II. Mathematical Modelling and Simulation Tools

A. Motorcycle model

The motorcycle mathematical model used for this study is a modification of an existing model of a Suzuki GSX-R1000. This model has been widely used in the past in several contributions in the field of motorcycle dynamics and stability analysis (see [5], [6], [7], [8]). It consists of seven bodies: rear wheel, swinging arm, main frame (comprising rider's lower body, engine and chassis), rider's upper-body, steering frame, telescopic fork suspension and front wheel. It involves 13 degrees of freedom: 3 rotational and 3 translational for the main frame, 2 rotational for the wheels spin, 1 rotational for the swinging arm, 1 rotational for the rider's upper body, 1 rotational for the frame flexibility, 1 rotational for the steering body and 1 translational for the front suspension fork. The tires are treated as wide, flexible in compression and the migration of both contact points as the machine rolls, pitches and steers is tracked dynamically. The tire's forces and moments are generated from the tire's camber angle relative to the road, the normal load and the combined slip using Pacejka Magic Formula models [9], [10] . For a detailed description of the complete model the reader is referred to [11].

B. *Interconeccion modelling*

In order to illustrate the interconnection concept in an intuitive manner, Fig. 1a) shows a sketch of an interconnection system where positive and negative values of the interconnection coefficients can be achieved. Fig. 1b) and Fig. 1c) show simpler arrangements where only negative or positive values are allowed respectively. In this approach, the coefficient sign will depend on the application point of the resulting interconnection force on the swinging arm.

The motorcycle original mathematical model has been updated to include the effects of the interconnection forces. In the original model, while the front suspension system is a telescopic fork and is described in the model as a lineal force applied to the front wheel from the main frame, the rear suspension consists in a swinging-arm and is described as a moment reacting between the main frame and this swinging-arm.

Following the approach in [12] the total force applied by the front telescopic fork is divided in both, standard and interconnection forces, which are defined independently. The suspension force depends linearly on the front fork position and speed, whilst the interconnection force does it on the rear swinging arm angle and rotational speed. For the rear end the force is modelled in a similar way. Equations (1) and (2) show the total front suspension force and rear suspension moment.

$$F = -k_f \cdot Z - c_f \cdot \dot{Z} - k_s \cdot \theta - c_s \cdot \dot{\theta} \qquad (1)$$

$$M = -k_r \cdot \theta - c_r \cdot \dot{\theta} - k_s \cdot Z - c_s \cdot \dot{Z} \qquad (2)$$

The variables Z and θ are the front fork displacement and swinging arm angle respectively. The parameters k_f(N/m) and c_f(N·s/m) are the stiffness and the damping coefficients for front suspension. The parameters k_r(N·m) and c_r(N·s·m) are the coefficients for the rear suspension. Finally the parameters k_s(N) and c_s(N·s) are the stiffness and damping coefficients for the interconnection system. Note that the units for the interconnection parameters already consider the conversion between angular displacement and linear force, and vice versa.

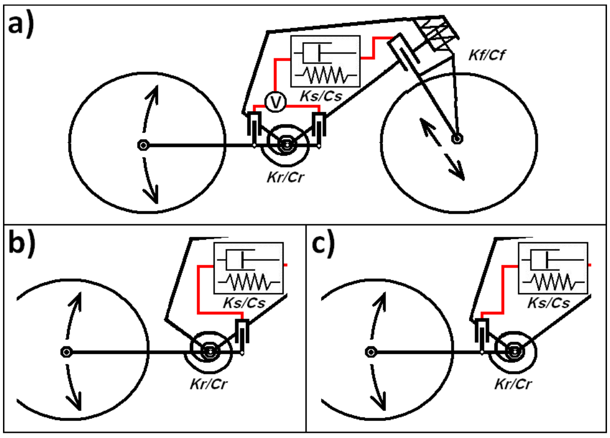

Fig. 1. Sketches of interconnected suspension systems. a) system for positive and negative values of interconnection parameters. b) system for negative values of interconnection parameters. c) system for positive values of interconnection parameters.

C. *Simulation tools*

VehicleSim is the software suit used to program and simulate the motorcycle model. It contains two important tools, VS-Lisp and VS-Browser. The first one is a set of LISP macros enabling the description of mechanical multi-body systems. One of the possible outputs from this program is a C-language project from which a dynamic-link library can be obtained. This library contains the model's equations of motion and it is used in the second program, VS-Browser. This other program is a powerful simulation tool that can integrate the model's equations of motion for different initial conditions, external perturbation or events such a road profile. Other output that VS-Lisp returns is a Matlab script with a state space description of the linearized model that represents a fundamental tool for the stability analysis.

VS-Browser is compatible with Matlab Simulink and allows performing simulations directly from Matlab. It becomes a useful tool for including external controller in the loop or to develop general purpose Matlab functions whose results depend on the simulation outputs. Fig. 2 shows an example of a Simulink model where the VehicleSim block is used to call a bump simulation which will be run from VS-Browser and whose outputs will be passed to the different Matlab functions. These functions can be either those used for mapping the response of the precision and comfort variables or the target functions set used in the optimization processes.

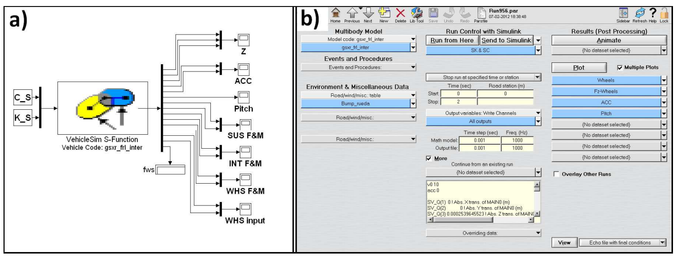

Fig. 2. a) Simulink model including VehicleSim Block to call a simulation that will be run from VS-Browser. b) VS-Browser simulation interface.

III. RESULTS

The two most important functions of a sport motorcycle suspension system are to provide enough precision for the wheels to follow the road profile as close as possible and to keep certain comfort levels for the rider even under road perturbation. In comparison with the preliminary work presented on [12], here we consider a nonlinear model where a discontinuity is introduced in the tires forces modelling, as a result, these forces become zero when the tires take off from the road. As it has been already explained in the introduction section, wheels fly times have been considered as a measurement for the suspension system's precision. For which shorter fly times will represent a greater precision. The comfort is studied through the maximum acceleration perceived by the rider and the maximum pitch angle reached by the motorcycle's main frame.

A. Efficiency Mapping

In order to investigate the effects of the interconnection force and moment in the suspension response, the behaviours of these four variables are studied under straight forward bump simulations for a wide range of stiffness (k_s) and damping (c_s) interconnection coefficients. The focus of this study is to understand the effects that the interconnection introduces in the response of the suspension, so the front and rear suspension coefficient are kept constant with their nominal values.

The 'efficiency on each variable' is defined as the normalized difference between the value achieved by the variable after a bump input with ($k_s \neq 0$ or $cs \neq 0$) and without ($k_s=0$ and $cs=0$) interconnection forces and moments. It is defined by (3) as follows:

$$Eff(x) = 100 \cdot (x - x_0)/x_0 \qquad (3)$$

Where x is the variable under study (it can be the maximum acceleration, the maximum pitch angle, the front wheel or the rear wheel fly times) and x_0 is the value achieved by the variable with non-connected suspensions. *Eff* is expressed as a percentage and will be positive if the connection arrangement provides a reduction on the variable's value.

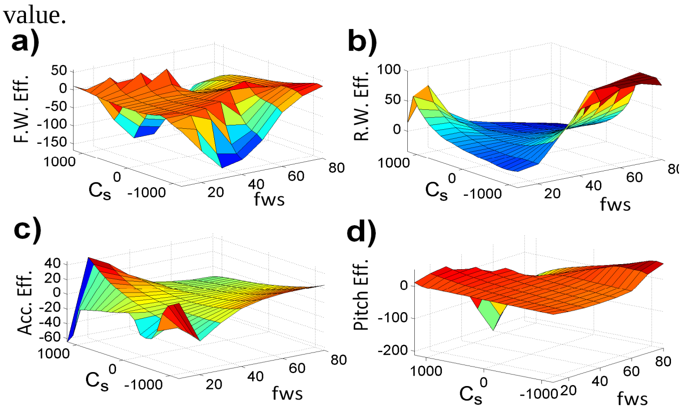

Fig. 3. Mapping of the efficiency on the comfort and precision variables for the different values of c_s with k_s=0 for a 0.05m step input at speeds going from 10m/s to 80m/s. a) Front wheel efficiency, b) rear wheel efficiency, c) acceleration efficiency and c) pitch efficiency.

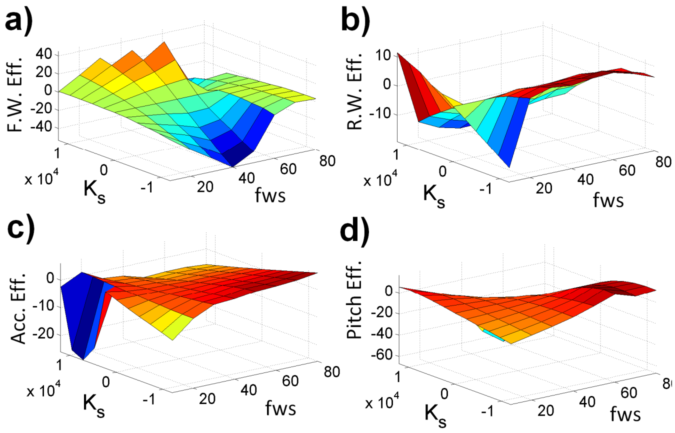

Fig. 4. Mapping of the efficiency on the comfort and precision variables for the different values of k_s with c_s=0 for a 0.05m step input at speeds going from 10m/s to 80m/s. a) Front wheel efficiency, b) rear wheel efficiency, c) acceleration efficiency and c) pitch efficiency.

Eight simulation environments have been prepared on VS-Browser for the eight forward speeds under study, starting at 10m/s and reaching 80 m/s. In theses simulations the motorcycle is forced to pass through a bump of 0.05m on the road at a constant speed. These environments are called from a Simulink model from where the stiffness and damping values are introduced. The Simulink model is placed in a loop where these coefficients are varied sequentially, performing all the simulations for values of k_s going from -12000 N to 12000 N and values of c_s going from -1200 N·s to 1200 N·s. With the results obtained we can map the efficiency on the comfort and precision variables.

Fig. 3 shows the result of varying damping c_s and the speed while keeping the stiffness k_s=0. It can be seen a difference between low and high speeds. For the low speeds, the front wheel efficiency can be improved with high positive and negative values of damping whilst for speeds higher than 40m/s only negative values are suitable.

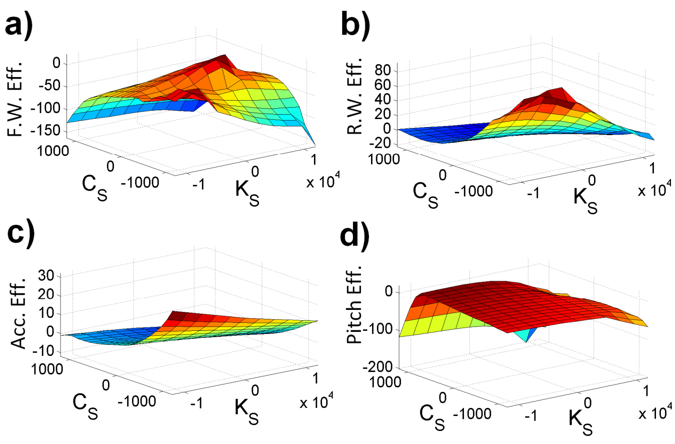

Fig. 5. Mapping of the efficiency on the comfort and precision variables for the different values of c_s and k_s for a 0.05m step input at a constant speed of 50m/s. a) Front wheel efficiency, b) rear wheel efficiency, c) acceleration efficiency and c) pitch efficiency.

For the other three variables, positive damping coefficients result in better efficiencies at low speeds, whilst for high speeds, the efficiencies are increased with negative values of c_s. Thank to this behaviour of the front wheel efficiency, a compromise solution with constant value of the damping coefficient that improve the overall performance of the suspension system can be found.

The stiffness variation presents a more complicated situation. The front wheel fly time efficiency is improve with positive values of k_s for speeds under 40m/s whilst for higher speeds negative values are needed. However, all the other 3 variables reach positive efficiencies only with negative stiffness values. This happens in all the speed range except for very slow (10 m/s) values. These results are shown in Fig. 4 where k_s and the speed are varied and c_s is kept equal to zero.

Finally the combination of stiffness and damping in the interconnection system becomes in a difficult scenario to find coefficients that improve the efficiency of all the variables at the same time. Automatic optimization processes have to be carried out in order to find these coefficients. Fig. 5 shows, as an example, the efficiencies mapping at 50m/s. Similar plots for all the forward speeds under study have been obtained and were used to choose good initial values for the optimization processes of the stiffness and damping.

B. Optimization

Considering that the model under study corresponds to a high performance racing motorcycle, the optimization process is focused on optimize the suspension precision, even if the comfort has to be sacrificed.

Matlab optimization toolbox is a good framework to find satisfying results with the minimum time resources. Different target functions are created to evaluate the front wheel fly time for a desired speed. This functions call to a Simulink model containing the VehicleSim Block, which is configured to run the VS-Browser simulation associated to this speed. The results of the simulation are processed to obtain the front wheel fly time which is passed to the fminsearch Matlab function as the target to be minimized.

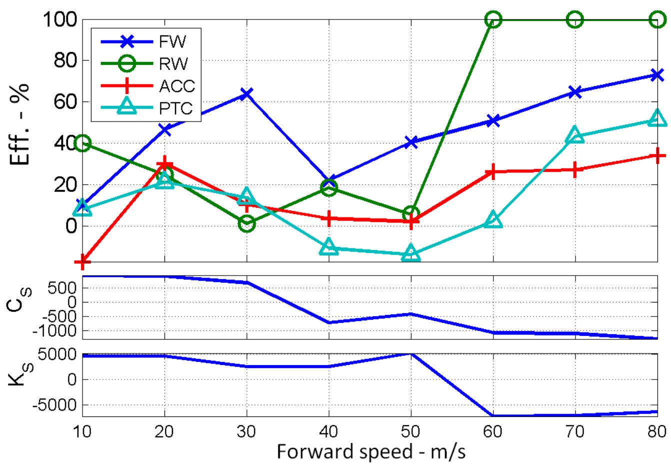

Fig. 6. Precision and comfort efficiencies for all the speed range for an interconnection system with optimal varying stiffness and damping coefficients.

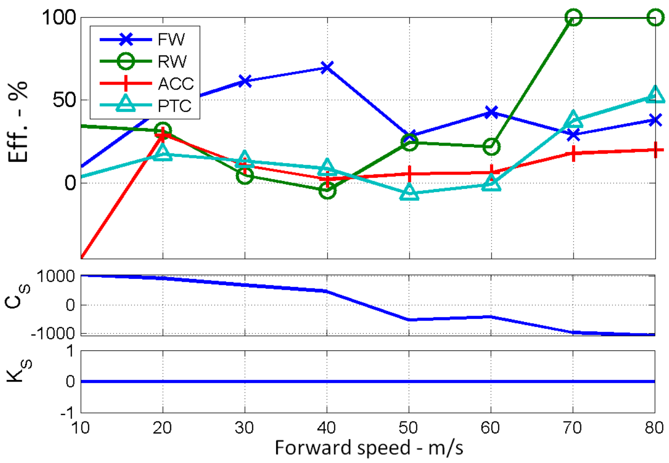

Fig. 7. Precision and comfort efficiencies for all the speed range for an interconnection system with optimal varying damping coefficient.

The results for four optimization processes considering four different mechanical arrangements are shown in Fig. 6 to Fig. 9 showing the efficiencies of the front wheel (*FW*), rear wheel (*RW*), acceleration (*ACC*) and pitch angle (*PTC*). The units of k_s are N and c_s is in N·s.

The first case, in Fig. 6, is for the full active interconnection system where k_s and c_s can take positive and negative values. High efficiencies of the front and the rear wheels are found for all the speed range.

The second case, in Fig. 7, is for semi-active interconnection for positive and negative values of c_s and k_s=0. The efficiencies are still very high for a much less complex system.

Fig. 8 shows the results of the third case, for semi-active interconnection system where c_s only can take negative values. The efficiencies now are not as high as the previous cases but the improvement of the responses can be already appreciated.

Finally Fig. 9 shows the case of passive interconnection system with one damper whose damping coefficient is constant and negative. The improvement percentage of the suspension response in the front wheel starts around 5% at low speeds and rises up to 17% at high speeds. The rear suspension response is highly improved for high speeds and slightly worsened for very low speeds, but never decays under the -7% efficiency. Considering that the front wheel is the most important in terms of riders control and that the rear wheel fly time is only increased for very low speeds, this is a good result for a very simple interconnection system. It has to be considered that this last optimization process has been carried out looking for a compromise solution for a wide range of speeds. If the motorcycle under study will be used in a more narrow speed range, such as street motorcycles, this implementation can returns even better results.

It has to be noted that in all the four cases the comfort is not worsened much, although the optimization processes have not taken it into account. For some speed and arrangement is even improved.

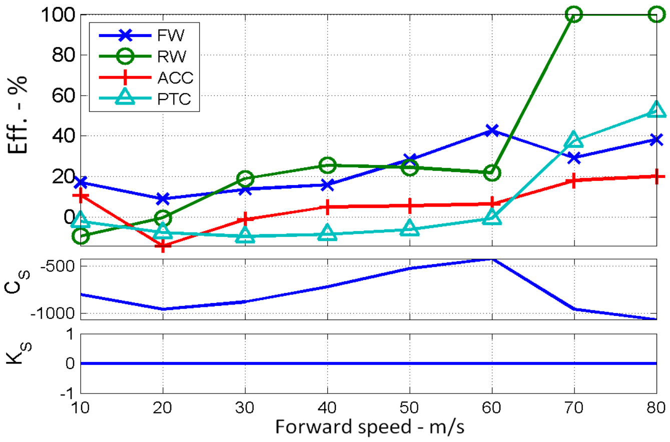

Fig. 8. Precision and comfort efficiencies for all the speed range for an interconnection system with optimal negative varying damping coefficient.

Finally Fig. 10 shows the response at 80 m/s for the last optimization. It is easy to see how the pitch angle and the fly times for both wheels are reduced whilst the maximum acceleration perceived by the rider reaches a similar value. The response of the independent system is marked with a dashed line and the interconnected system with a solid line.

C. Stability

When structural modifications are introduced in a complex dynamical system such as a motorcycle, its stability can be compromised. Taking advance of the state space description provided by VS-Lisp and following a similar approach than in [13], several root locus for all the range of the stiffness and damping interconnection coefficients have been obtained.

As an example, Fig. 11a) shows the root locus for the motorcycle with non interconnected suspension starting at a speed of 10m/s (□) and reaching 80 m/s (*) at roll angles of 0^o (blue x), 15^o (green o), 30^o (red +) and 45^o (black ◊). Fig. 11b) shows the same simulation for the motorcycle with optimal interconnection damping coefficient of -548 N·s.

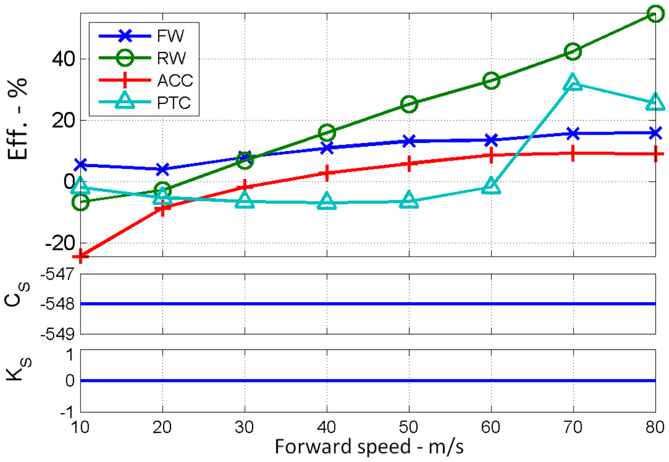

Fig. 9. Precision and comfort efficiencies for all the speed range for an interconnection system with optimal constant damping coefficient.

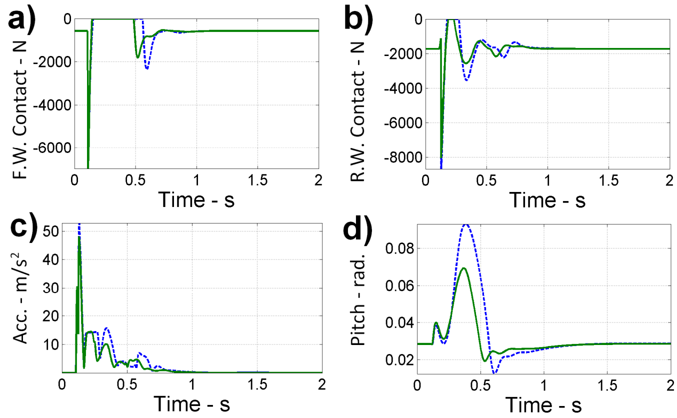

Fig. 10. Response of the precision and comfort variables at 80m/s with an interconnection damping coefficient of -548 N·s.

It can be observed three out-of-plane modes near to the stability limit that remains almost unaffected by the interconnection. These are the capsize, the weave and the wobble (going from low to high frequency respectively). Two in-plane modes that, for the nominal case, are highly damped can be seen. These modes are related with the pitch and bounce motion and the interconnection system displace them towards the right in the real plane. However they stay stable, even more than the out-of-plane modes, at any speed.

For the other optimized configuration, the roots of the in-plane modes take much wider areas of the root locus and the different modes become more difficult to be identified. Nevertheless, none of these roots gets the unstable region. Resulting that, for all the possible configurations, the different interconnection proposals do not represent any stability risk.

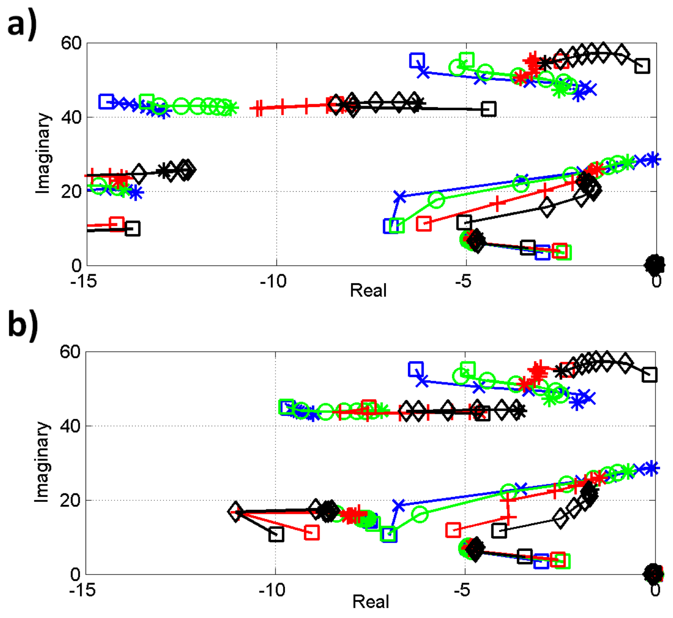

Fig. 11. Root locus for two motorcycle models fitted with a) independent suspensions and b) interconnected suspensions. Speed is varied from 10m/s (□) to 80m/s (*). Different roll angles are considered: 0^o (blue x),15^o(green o), 30^o (red +) and 45^o (black ◊).

IV. Conclusions

This work presents the potential benefits in terms of suspension precision and comfort that an interconnected suspensions system could introduce in a motorbike, if it is adequately implemented.

For the motorbike model under study, it has been shown that satisfactory results are achieved in terms of tyres fly time reduction by the connection of the front and rear suspension, just by means of a simple damper unit. By increasing the complexity of the mechanical system, better results can be achieved if it is possible to modify dynamically the stiffness and damping interconnection coefficients.

It has been found that positive damping connection coefficients are more adequate for the band of low speeds. For the high speeds, negative values are needed. The work presented in here considered a wide speed range. For more narrowed speed ranges, better result can achieved just by a simple device that connect the front and the rear suspension with a constant coefficient damper.

The stability of the system has been also studied to ensure that this type of modification does not introduce dangerous instabilities to the motorcycle system. The eigenvalue analysis shows that, as expected, only the in-plane modes are affected for all the speed and pitch angle ranges, and they do not get significant low damping values.

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