Dynamical Analysis of a Duolever Suspension System

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Abstract — **The authors investigate the dynamical behaviour of a Duolever type of suspension on a standard sports motorcycle. The paper contains the modelling aspects of it, as well as the optimization process followed in order to obtain the suspension parameters and geometry arrangements. Head angle, wheelbase and normal trail are studied as indicators of the handling properties of the suspension system. Matlab optimization toolbox was used to design a mathematical model of a duolever front suspension system which keeps its normal trail constant during the full suspension travel. By using VehicleSim software, non-linear simulations were performed on motorcycle model that includes a duolever suspension. By a quasi-static variation of the forward speed of the motorcycle, the time histories of the system's states were obtained. The corresponded root locus to the linearized model were plotted and compared to those of the original motorcycle model without duolever system. A modal analysis was performed in order to get a deeper understanding of the different modes of oscillation and how the duolever system affects them. The results show that whilst a satisfactory anti-dive effect is achieved with this suspension system, it has a destabilizing effect on pitch and wobble modes.**

Keywords- Modelling; motorcycle; weave; wobble; suspension; Hossack; Duolever

I. Introduction

One of the most important factors on motorcycle stability is the front end. It links the front wheel with the main frame and has two main functions: the suspension of the front wheel and the steering of the motorcycle. Up to this date several suspension systems have been developed to reach the best behaviour of the front end, being the telescopic fork the most extended one. The Hossack/Fior (marketed as Duolever), decouples the suspension and steering functions. One of its advantages is that it can be designed to achieve a desirable performance when suspension action takes place in terms of wheelbase, trail and head angle. The purpose of this paper is to study the effect of a Duolever suspension system on the dynamical properties of high performance motorcycles. Making use of Duolever's configurable properties in terms of wheelbase, head angle and trail, an eventual alternative front suspension is designed. This is done making use of the mathematical modelling and simulation of a motorbike. It will predict the behaviour of the various systems and help to decide which one is the most appropriate as base of the alternative front suspension system. The authors base this work on an existing high fidelity model of a Suzuki GSX-R1000, extensively used and validated in previous research (see [1], [2] and [3]),. The suspension system is designed by using algebraic methods to ensure as a first approach that similar properties and parameters to the original design are kept so that they can be compared under equal conditions. This is; similar head angle, trail, masses and inertia, etc. Later on, parameters such as mass or inertia will be varied -always within the limits of engineering constrictions- to study their influence on the motorcycle's dynamical properties.

The structure of this paper is as follows: Section II introduces the high-fidelity motorbike mathematical model which forms the basis of this work including a description of the modelling software VehicleSim. Section III contains an explanation on the Duolever system. Parametrization methodology, optimization of the parameters and suspension behaviour are also included. Section IV discusses on the oscillation modes and stability issues arising from the Duolever suspension. Finally, the results are discussed in section V and some future research ideas are presented.

II. Model Description

The model used is based on an existing model of a Suzuki GSX-R1000 used in the past for several contributions in the field of motorcycle dynamics and stability analysis (see [4], [5], [6], [7], [8]). It consist 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 assembly. It involves three translational and three rotational freedoms of the main frame, a steering freedom associated with the rotation of the front frame relative to the main frame and spinning freedoms of the road wheels. The road 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 tyre's forces and moments are generated from the tyre's camber angle relative to the road, the normal load and the combined slip using Magic Formulae models [9] and [10]. This model is applicable to motorcycle tires operating at roll angles of up to 60^{o}.The aerodynamic drag/lift forces and pitching moment are modelled as forces applied to the aerodynamic centre and they are proportional to the square of the motorcycle's forward speed. In order to maintain steady-state operating conditions, the model contains a number of control systems, which mimic the rider's control action. These systems control the throttle, the braking and braking distribution between the front and rear wheels, and the vehicle's steering. For a detailed description of the complete model the reader is referred to [3]. It has been developed using VehicleSim [11], it is a set of LISP macros, enabling the description of mechanical multi-body systems. The outputs from VehicleSim are a simulation program based on "C" language with the implementation of the equations of motion and a Matlab [12] file containing the model's linear state-space equations. VehicleSim commands are used to describe the components of the motorcycle multi-body system in a parent-child relationship according to their physical constraints and joints. Once the VehicleSim code generates the simulation program, this is capable of computing general motions corresponding to specified initial conditions and external forcing inputs.

III. DUOLEVER SUSPENSION SYSTEM

Following the scheme of double wishbone car's suspension systems, the Duolever suspension for motorcycles consists of two wishbones, one upright and a steering linkage. The wishbones can rotate around transverse axes and the upright is now a fork in which the front wheel is attached. In the car version the wheel spins in a perpendicular axis due to the position of the system which is placed in the side of the car. In the bike case, the system is placed in the front, so the wheel has to be rotated 90 degrees with respect to the car wheel. The connection of the fork with the two wishbones is made by ball joints which allow the wishbones rotate and the fork turns in the steering axis. The steering axis is defined by the ball joints centres. The steering linkage connects the handlebar with the fork. It is a system of two levers, connected by an axis, which can be compressed or elongated in order to reach the length between the handlebar and the fork. See [13] and [14] for more detailed information about Duolever systems. Fig. 1 shows a schematic CAD design for a standard motorcycle fitted with a Duolever system: the different structural points of the duolever and the parameters defining its geometry have been marked in red. The spring-damper unit has not been included to help a clearer view.

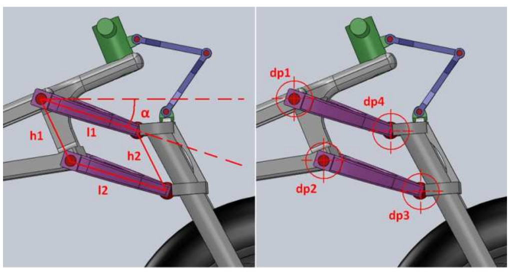

Figure 1. 3D kinematic components of a Duolever system. Parameters and points defining the Duolever geometry.

A. Parametrization

The position of all the points is calculated in order to keep the model as close as possible to the configuration of the original motorbike described before. First of all, the parameters which must be considered in the design of the system the Duolever must be defined. These parameters are *l1*, *l2*, *h1*, *h2* and α. Where *l1* and *l2* are the lengths of the upper and lower wishbones, *h1* is the distance between the attachment points of the upper and lower wishbone, *h2* is the distance between the tips of the upper and lower wishbones and α is the nominal angle formed between the upper wishbone and the horizontal. With these parameters and the head angle the Duolever system is defined. The question is to find the attachment point to the main frame. To simplify this task the model of the motorbike is reduced to four main bodies: rear frame, front frame and two wheels. Two axes are considered: the rear-axis is the axis from the rear wheel attachment point to the point of attachment of the conventional front fork and, the front-axis, starting at this same point and forming the head angle with the vertical. The main points defined are:

dp1: attachment point of upper wishbone in main frame.

dp2: attachment point of lower wishbone in main frame.

dp3: tip of the lower wishbone.

dp4: tip of the upper wishbone.

dp5: spring-damper unit in lower wishbone.

dp6: spring-damper unit in main.

pts: point located at the origin of the twist body in GSX-R1000 model when telescopic fork suspension was used. Now it is an auxiliary point located at the same position.

In order to not modify the steering axis of the original model, *dp3* and *dp4* should be located on the front-axis and *dp1* is placed in the rear-axis to keep the delta-box configuration. Fig. 2 shows these points in the geometrical model.

B. Optimization

1) Suspension behaviour:

There exist four main parameters that mainly affect motorcycles´ handling. These are the wheelbase, the head angle, the trail and the normal trail. Wheelbase is the distance between the front wheel contact point and the rear wheel contact point. The head angle is the angle existing between the steering axis and the vertical axis. The trail is the distance between the front wheel contact point and the intersection of the steering axis with the road's plane. Finally, the normal trail is the distance between the front wheel contact point to the steering axis; it depends directly on the head angle and is just a perpendicular projection of the trail:

$$ntrail = trail \cdot \cos(H_{ang})$$

For a Duolever suspension system the behaviour of the trails, wheelbase and head angle under suspension actuation depends on its design.

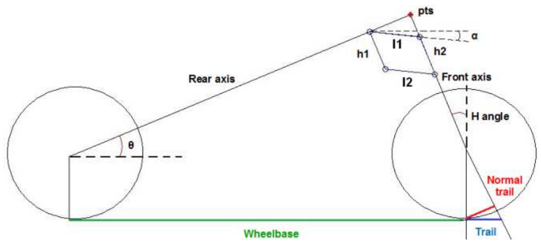

Figure 2. Points and angles defining the models geometry. Trail, head angle and wheelbase shown.

Whilst for a telescopic fork suspension system it is not possible to modify this behaviour, in a Duolever system the parameters *l1*, *l2*, *h1*, *h2* and α can be optimized in order to modify it. Fig. 3 shows this concept. For the (simplest) case of a parallelogram structure, the same result as for the conventional fork can be obtained due to the steering axis remains parallel to its initial direction along the full suspension travel.

2) Parameters variations:

The starting point for the optimization of the Duolever is to study the variation of the wheelbase and the normal trail with the suspension action. A geometrical model has been implemented on Matlab so that it allows tracking the eventual position of all the points in the assembly motorbike-Duolever along with the suspension travel, once the nominal position is known. The nominal position of the points *dp1*, *dp2*, *dp3* and *dp4* are given by the values of geometrical parameters. Considering the geometrical limitation of the motorcycle under study we took as a good approach the following values: *l1=170mm*, *l2=170mm*, *h1=120mm*, *h2=120mm* and α*=0.1rads*. A variation between the maximum and minimum α values (which have been calculated in order to produce an equivalent displacement of the motorbike as the conventional fork does) is performed, obtaining the geometrical position of all the points along the suspension travel. In Fig. 5 it is shown (dashed blue line) the behaviour of the wheelbase and the normal trail with the vertical suspension travel using the nominal set of parameters. Finally, in order to see how this behaviour changes according to Duolever parameters' variation, an external function has been developed. It takes an initial parameters vector and varies in a loop the parameter selected by the user. This loop calculates and stores the values of wheelbase and normal trail along the suspension travel for every value of the parameter varied. As an example, the 3D meshes representing the results obtained from the variation of geometrical parameter α, *l1* and *l2* are shown in Fig. 4. An *xz* reference axis that shows the nominal configuration is included in the figures.

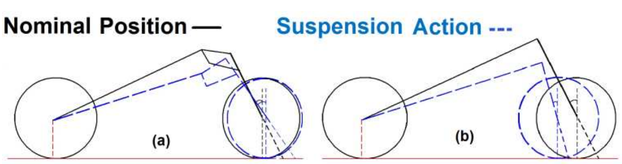

Figure 3. a) Duolever suspension system, head angle trail and wheelbase increase with the travel of the suspension. b) Telescopic fork suspension. Head angle, trail and wheelbase decrease with the travel of the suspension.

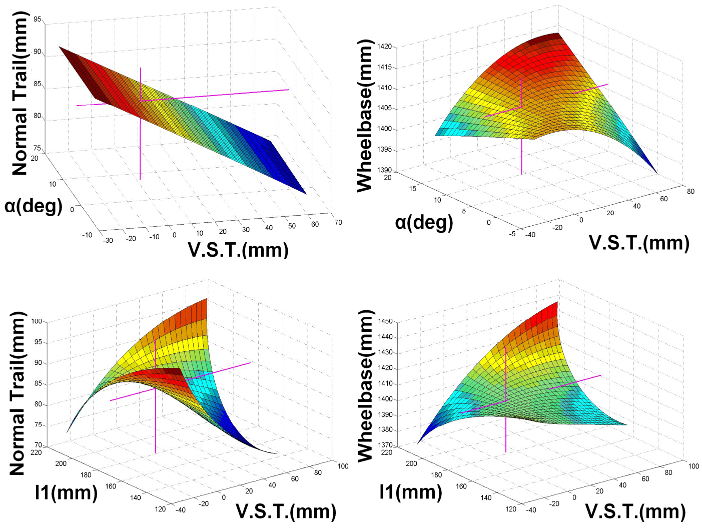

Figure 4. Behaviour variation with vertical suspension travel when parameters α and *l1* are modified.

As it can be seen, the variation with the parameters change is complicated enough to dissuade us to attempt a manual setting of them if we want to get constant trail or wheelbase. An automated optimization process is clearly needed to resolve this task.

3) Optimization process:

The goal is to find an optimal Duolever's parameter set such that the front suspension keeps the normal trail (so the trail and head angle) as constant as possible. A target function is defined and minimized by using Matlab optimization toolbox. This target function is the maximum difference -for a full suspension travel- between the nominal normal trail and the new normal trail depending on the set of parameters.

$$target = max(abs(ntrail-ntrail0))$$

Fig. 5 shows the behaviour of the wheelbase and normal trail for the optimized set of parameters in a solid green line. The values of these parameters are *l1=171mm*, *l2=182mm*, *h1=105mm*, *h2=124mm* and α*=0rad*. The nominal values of normal trail and wheelbase are plotted in dotted red lines. It can be seen how the lines for the optimized and standard Duolever cross each other at the initial value of the normal trail and the wheelbase but then their behaviour change completely. It is clear that the optimized set of parameter reduces almost to zero the variation in normal trail of the Duolever system.

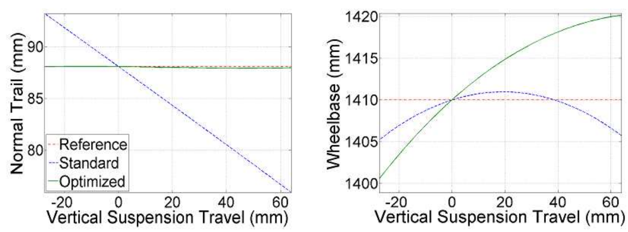

Figure 5. Wheelbase and normal trail behaviour with the vertical suspension travel for the geometrical standard and optimized models.

However, because we have used as target function the variation of the normal trail, the wheelbase is not kept constant but increases with the vertical suspension travel. Nevertheless this variation represents less than 1% and is not considered to be representative enough.

IV. Oscillatory Modes and Stability Issues

One possible consequence of introducing new features and geometry changes in a motorcycle is that the stability of the system can be severely compromised. Motorbikes are nonlinear, oscillating complex systems that can represent a risk if they are not well damped. The modes under study are wobble and weave (see [4] for more details on these two modes). In this section the stability of the motorcycle model fitted with a Duolever type of suspension is analyzed by means of root locus diagrams in a similar manner as previous works such as [5], [6], [7] and [8]. Once the model with the optimized Duolever is built in VehicleSim, nonlinear simulations under different running conditions are performed and the linearized state space matrices of the system are fed with the nonlinear simulations states values in order to study the evolution of the eigenvalues over the operating envelope. Fig. 6 represents the root locus for the GSX-R1000 model with a telescopic fork (red +), a standard (blue x) and an optimized (green o) Duolever suspension systems. The roll angle for these simulations is 0 degrees and the swept variable is the forward speed ranging from 10 up to 80m/s. The stability properties of three characteristic modes will be analyzed: weave, wobble and pitch.

There are two main differences between the Duolever and the telescopic fork root locus plot. The wobble mode becomes unstable at medium speeds when a Duolever suspension is fitted in the model. Also, it can be seen that a "new" eigenvalue appears. This corresponds to the pitch mode. In the case of the telescopic fork it did not appear as it was well damped and greatly displaced on the left hand side of the complex plane. It lightly differs from the optimized and the standard Duolever models.

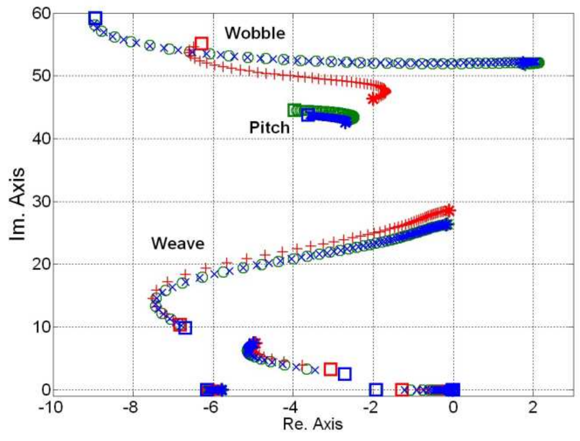

Figure 6. Root locus of the motorbike fitted with a telescopic fork (red+), a standard (blue x) and an optimized Duolever (green o) for 0 degrees of roll angle and a speed going from 10 (squares) up to 80 m/s (stars).

In order to find what eigenvalue it was and where it came from, the eigenvectors of the model with the Duolever system were compared with the eigenvectors of the model with telescopic fork system. As the eigenvalues for the optimized and standard Duolever models are very similar the comparison between eigenvectors has been done only for the optimized Duolever model. The comparison in Fig. 7 shows the modulus of the components of the eigenvectors. Only the generalized speeds are shown on the bar diagram. On the left side for each component, the value for the optimized Duolever is shown in green and on the right; the correspondent value to the telescopic fork is shown in red. The components of each eigenvector are labelled as follows:

XT, YT, ZT:	*Translation of main body.*
XR, YR, ZR:	*Rotation of main body (Roll, Pitch, Yaw).*
RSP and FSP:	*Compression of rear and front springs.*
RW and FW:	*Rotation of rear and front wheel.*
UBR:	*Rotation of riders´ upper body.*
STR:	*Rotation of steer axis.*
TWS:	*Rotation of twist axis.*

It has to be noted that the Duolever mathematical model was defined without flexibility, that means that it will have not twist degree of freedom, hence this coordinate will only appear for the telescopic fork model. It can be seen that there exist a high symmetry between the modes of the telescopic fork and the optimized Duolever models. There is a similar pattern in their components except for the twist generalized coordinate. For the Duolever case the twist degree of freedom has not been included, leaving this for the next step of this research.

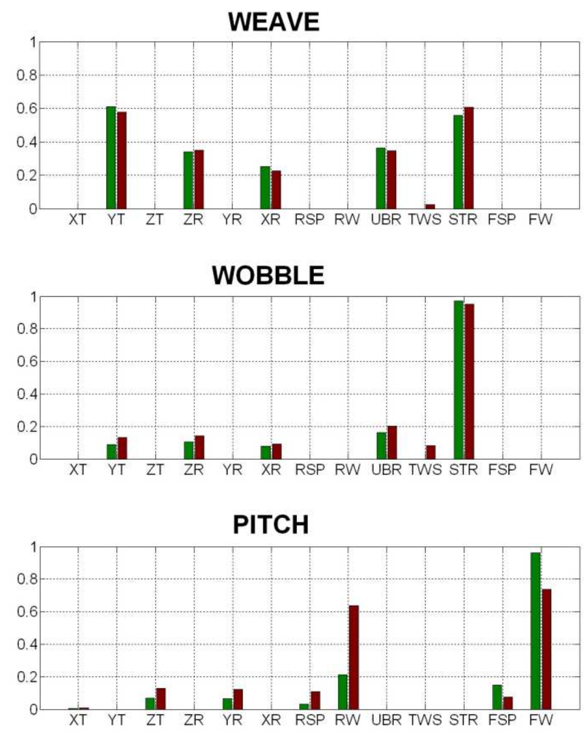

Figure 7. Eigenvector components for weave, wobble and pitch modes. Duolever suspension in green on the left, telescopic fork in red on the right.

Weave and wobble are out-of-plane modes. For both Duolever and telescopic fork cases, it is shown that the contribution of the various degrees of freedom to their eigenvectors is similar. On the other hand, pitch is an in-plane mode, the oscillation takes place in the symmetry plane of the motorbike, but for the Duolever case, the front wheel contribution becomes more relevant than in the fork suspension case whilst the contribution of the rear wheel is less. Also the front suspension coordinate increases its relevance and rear suspension decreases it. Finally the amplitude for the rotation in *y* and translation *z* (which implies the pitching of the main body) is reduced. Considering this, we can think of an oscillation about the front wheel which cannot be damped effectively by the front suspension. In order to check this, several simulations have been performed introducing various values of front tire damping coefficient. Fig. 8 shows these results for various values of damping. The weave and wobble modes appear as in Fig. 6 for both the telescopic and Duolever cases. The pitch mode appearing for the Duolever case changes according to various values of front tyre damping coefficient.

In the light of results shown in Fig. 8, it can be seen how the Duolever suspension does not damp pitch oscillations as effectively as the fork suspension does. This is a consequence of the Duolever's geometry and the anti-dive effect that it provides, reason why a Duolever suspension does not dive whilst performing braking action. The front assembly has a main role in the motorbike dynamic and in the case of the Duolever model its design becomes relevant for the pitch mode. In order to illustrate this, a straight running, front wheel braking simulation was carried out. The vertical suspension travel is shown in Fig. 9.a and the pitch rotation of the main body is shown in Fig. 9.b. The force applied in the front brake was calculate to provide the same deceleration of 1.5m/s^2 for all the three cases: telescopic fork (red), standard (blue) and optimized Duolever (green).

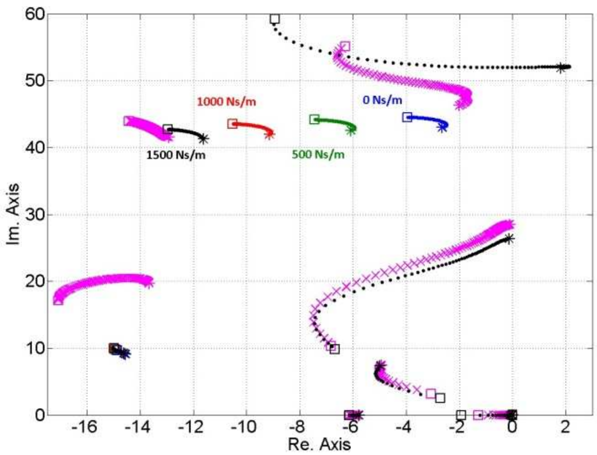

Figure 8. Root locus for the model of the motorcycle fitted with a telescopic fork (magenta +) and an optimized Duolever (blue ▪, green ▪, red ▪ and black ▪) for 0 degrees of roll angle and speed being swept from 10 (squares) up to 80m/s (stars). The damping of the front wheel is varied from 0 Ns/m up to 1500 Ns/m.

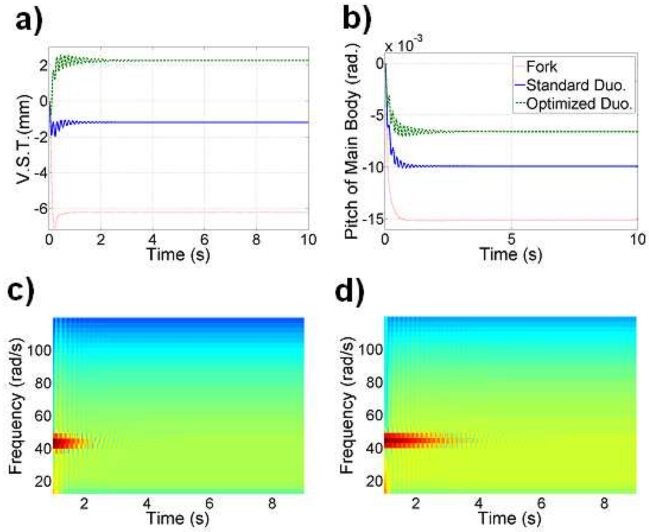

Figure 9. a) Vertical Suspension Travel for a braking simulation of 1.5m/s^2, b) Pitch of the Main Body for a braking simulation of 1.5m/s^2, c) Spectrogram of the Vertical Suspension Travel for the standard Duolever model during the braking simulation, d) Spectrogram of the Vertical Suspension Travel for the optimized Duolever model during the braking simulation.

It can be seen how whilst the front fork dives about 6mm, the standard Duolever does it only less than 1.2mm and the optimized Duolever does not dive but rises about 2.2mm. This behaviour appears due to the Duolever geometry which was optimized to get a constant trail. Other effect seen in this figure is the oscillation for Duolever systems, being higher and larger in time for the optimized one. In order to get a better understanding a spectrogram of the signal was done. It was used a 2 seconds time window with an overlapping of 99% to get good compromise between time and frequency resolutions. The low and high frequency components were neglected in this plot. The results are shown in Fig. 9.c for the standard and Fig. 9.d for the optimized Duolever. Due to the size of the window (2 secs.) the spectrograms for the first and the last seconds cannot be displayed. However, in both plots, oscillations about 43rad/s can be clearly recognized, they propagate reducing their amplitudes until they disappear. It can be seen how for the optimized Duolever the oscillation is sustained up to 4 seconds, whilst for standard Duolever model it disappears about 2.5 seconds.

The root locus plots showed that the frequency of the pitch mode is around 43rad/s at 80m/s, which is the initial speed of the motorcycle in the braking simulation case. This mode that becomes less stable with the Duolever front suspension system is prone to affect the behaviour of the motorcycle, representing a handicap for these type of suspension systems.

From these simulations it is clear to see that fitting a Duolever suspension system produces instability in the wobble mode. Wobble mode depends mainly on three factors that need to be taken into account: the mass and inertia of the front assembly and the damping ratio of the steering damper. If a high value of damping ratio is used, a more stable steering will be found at high speeds but it will be much less manoeuvrable at low speeds. Also, as it has shown in [6], increasing the steering damping coefficient the weave mode becomes less stable. Several commercial motorcycles with telescopic fork suspensions include steering dampers whose damping coefficients are variable with the speed. At the moment, the authors are investigating the possible benefits of including a speed dependant steering damper in the case of a Duolever suspension type. These results will be presented in a separate report.

V. CONCLUSIONS

The mathematical model used for this study corresponds to a Suzuki GSX-R1000. This motorbike is not fitted with a Duolever, it is designed to make use of a telescopic fork. The mathematical model was modified with a carefully designed new suspension system model based on reasonable assumptions. Some dynamical properties about this type of suspension system have been studied.

The Duolever suspension can be designed in order to get a determined behaviour of the wheelbase, the head angle or the trail and the normal trail. In this study, a configuration which provides a constant normal trail along all the suspension travel for a Duolever system was obtained.

In general, a Duolever suspension system provides an anti-dive effect due to tyre's contact patch curvilinear trajectory. One of the consequences of the optimization of the Duolever is the increased anti-dive effect that appears compared to the standard Duolever suspension with a parallelogram design.

The anti-dive effect would represent in most cases beneficial characteristics but, in terms of oscillating behaviour, the pitch mode becomes clearly less damped compared to the case of standard telescopic fork suspension, representing in this way a possible risk issue under certain running conditions.

The advantages of the Duolever suspension system are meant to be the comfort, the manoeuvrability and the better performance of the front suspension, keeping the trails almost constant for all the suspension travel and presenting a relevant anti-dive effect. This allows the suspension to be fully operative on braking. However, it has been shown that less stable pitch modes are associated to this system.

It has also been shown how after including this suspension system in the model of a motorcycle which has not been designed to fit this type of suspensions, the wobble mode becomes unstable at high roll angles and medium-moderate speeds. In order to get wobble stability for the Duolever case, possibly a more complex steering damper unit depending on the speed should be design, or an inerter could be included. These possible solutions are currently under investigation by the authors.

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