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Motorcycle Dynamic Stability Monitoring During Standard Riding Conditions

F. Cheli, M. Pezzola, E. Leo, T. Ibrahim, A. Saita

Department of Mechanical Engineering
Politecnico di Milano
Via La Masa 1, 20156 Milan, Italy
e-mail: marco.pezzola@polimi.it

ABSTRACT

The target of the research is to improve driver safety related to dynamic instability, often cause of accidents involving powered two-wheeled vehicles as explained in the "UNECE Transport Review of Road Safety" ([1]). The paper explains the feasibility study of an Advanced Driver Assistance System (ADAS) with regards to the real-time instability conditions identification of a generic motorcycle during standard riding conditions. As well known, these types of systems have been typically applied and relied on in the automotive sector, but they have not yet broken through for two-wheeled vehicles. An initial study of the vibration modes of a motorcycle led to the isolation of the weave mode and the wobble mode ([2]) as the most likely to occur during normal use. Having identified the damping factor of the vibration modes as a possible instability index, various methods have been studied to estimate the frequency and damping coefficients of the weave and wobble modes. The methods considered include both one DOF system methods and a multi DOF system method. Each of these have been evaluated on a numerical time history and an experimental time history. In particular the accuracy, robustness, time efficiency and ease of implementation have been considered as a priority in choosing the most effective method. A logical procedure with which a possible dynamic instability can be identified is therefore reported and explained. The developed intelligence has been integrated in an offline diagnostic software that processes signals acquired by sensors placed on the motorcycle during running. Using this algorithm logic two very different motorcycles have been studied and a comparison between experimental and numerical results are shown. The proposed methodology has also been implemented in a GUI (Graphical User Interface), whose scope is to emulate the real-time application of the algorithm logic to standard running conditions.

Keywords: motorcycle stability, motorcycle safety, weave, wobble, ADAS.

1 INTRODUCTION

The last few years have seen an increase in the interest of research topics regarding two-wheeled vehicles. Research conducted in this area has identified various engineering related problems associated with these types of vehicles, and in particular for what concerns comfort, handling and safety. This last area is always more at the centre of attention of the various motorcycle and apparel manufacturers.

This work is connected with the research activities regarding the stability of the dynamic behaviour of a motorcycle and in particular will analyse in detail the effect of a dynamic instability on safety. As explained by Cossalter in [2], the motorcycle is a complex strongly non-linear mechanical system that presents many difficulties in assessing the behaviour while in motion. This behaviour of the motorcycle can be observed experimentally as oscillations that include both the

front assembly and rear assembly in a singular or combined motion. The driver, due to the movements and moment applied on the steering assembly during motion, can actively modify the mechanical characteristics of the overall system as explained by Sharp in [3]. Due to the aim of this work, which is to monitor the stability of the motorcycle with a driver in real-time, a fixed control (driver input present) is considered. In [4] Cossalter explains that a two-wheeled vehicle has eight significant modes of vibration which are included both in the in-plane and out-of-plane modes. The in-plane modes include bounce, pitch, front hop and rear hop, whilst the out-of-plane modes include weave 1°, weave 2°, wobble and capsize. The out-of-plane modes are fundamental for the study of the stability and handling of the motorcycle and are therefore the modes of vibration that are of the most interest. In straight running the in-plane and out-of-plane modes are uncoupled, and can therefore be studied separately, while during cornering the modes tend to couple due to the camber angle and so the frequencies and damping factors of the vibration modes can change ([5]).
The major causes of accidents involving road vehicles is due to driver error, lack of adequate infrastructure and instability phenomena of the vehicles, as explained in the [1]. This is highlighted to be more of a problem in certain countries respect to others where there is a high concentration of road users with poor road infrastructures. The use of ADAS (Advanced Driver Assistance Systems), which are able to foresee, reduce or eliminate various life threatening situations for the driver by offering useful information can be an important step in reducing accidents.

In the field regarding two-wheeled vehicles an increase in the awareness of the benefits of such systems is slowly emerging. In [6] the use of a Spanish accident database allowed the study of the benefits of integrated ADAS systems and the results showed, for each accident typology, the possible ADAS/IVIS (In-Vehicle Information Systems) systems that could be useful in avoiding that particular accident in future. The *SAFERIDER project* [7], an EU Commission funded project that includes 20 partners from 9 European Countries including some of the major manufactures of motorcycles and scooters worldwide, is deemed to be the first concrete step towards the implementation of these systems on two-wheeled vehicles. The aim is to study the potential of ADAS/IVIS integration on motorcycles for the most crucial functionalities and develop efficient and rider-friendly interfaces. The main functionalities that have been studied during this work are intersection support, frontal collision warning, curve warning and speed-alert warning. Cossalter in [8] shows how a motorcycle simulator, can be used to develop and test rider assistance systems before effectively launching them on the market. In particular, the riding simulator is used for testing and developing ADAS devices such as those of the *SAFERIDER project*.

The present paper presents a methodology useful in the identification of instability phenomena that two-wheeled vehicles can be victims of. Sharp's numerical four degree of freedom motorcycle model has been used to evaluate the potentiality of the various identification methods and for comparison with the experimental results. The model is linearized in straight running conditions. In the paper a description of the experimental tests that were conducted is reported, including a description of the various sensors used. The proposed algorithm logic for the identification of instability phenomena, with the aim of real-time application, is explained. An overview of the various frequency and damping identification methods is therefore provided. The positive and negative aspects of each of these methods are also presented. A numerical-experimental sensitivity analysis, where some of the fundamental parameters that influence the dynamics of the motorcycle are varied, is presented. This includes variations of the front trail, the removal of the steering balances, lowering of the front and rear tyre pressures, variation of the suspension settings and of the steering damper. The last section shows the application of the proposed methodology in a real-time application. In particular, using a GUI (Graphical User Interface), an emulator is created to test the real-time capabilities of the algorithm logic.

2 NUMERICAL MODEL

The vehicle model used in this thesis is the one proposed by Sharp ([9]) and allows a description of only the lateral dynamics of the two-wheeled vehicle. A complete description of the model is available in [10] and [11]. The vehicle is schematized as two rigid bodies, “front assembly” and “rear assembly”, linked at the steering axis by a revolution joint. The suspension, pneumatic tyre and the chassis deformability are not considered in this model. This model is used only with the aim of studying the vehicle stability in linearized conditions, for small oscillations, in straight running at a constant speed. On the vehicle two mobile reference systems are represented: one is fixed to the front body (x_f - y_f - z_f) with origin in O_f, the front body’s centre of mass, with z_f axis parallel to steering axis while the second is fixed to the rear body (x_r - y_r - z_r) with origin in O_r, the ground projection of the centre of mass of this body. There is a global reference system (*X* - *Y* - *Z)* that in undisturbed vehicle conditions coincides with the reference system fixed on the rear body (see Figure 1).

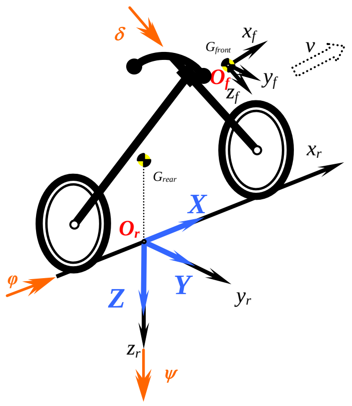

Figure 1 - Sharp’s motorcycle 4 d.o.f. model.

To describe the lateral dynamics of the motorcycle, four degrees of freedom are used:

- lateral movement *y* of the rear body centre of mass with respect to the global reference system, or better, the translation along the *Y* absolute axis;
- yaw angle ψ measured respect to the rear body reference system, or better, the rotation around the axis z_r;
- steer angle δ measured respect to the reference system fixed to the front body, or better, the rotation around the steering axis parallel to the axes z_f;
- roll angle φ measured respect to the reference system fixed to the rear body, or better, the rotation around the x_r axis;

The equations of motion associated to the four degrees of freedom are dependant on various characteristics unique to each two-wheeled vehicle. The motorcycle geometry, such as the distances that define the position of the centre of mass of the front body and rear body, the wheelbase and the front trail are important, as are the mass and inertias associated to the front and rear assemblies around the various reference axes and the tyre characteristics, such as the toroidal radius, the roll radius and the slip and roll stiffness of the front and rear tyre. The dynamics of the lateral forces generated are modelled using a first order differential equation. The effect of a steering damper is also considered and a steering torque to take into account the presence of the driver is present. A proportional-derivative controller (PD) on the roll angle φ is used for this scope.

This numerical model has been applied to a sports motorcycle and a scooter. The more significant values of the parameters that characterize the two motorcycles in the numerical model are shown in Table I.

Parameters	Scooter	Sports Motorcycle
Front mass [kg]	32	45
Rear mass [kg]	136	210
Normal front trail [m]	0.124	0.102
Wheelbase [m]	1.438	1.408
Distance between front body centre of mass and rear body centre of mass [m]	0.864	0.9

Table I - Values of the front mass, rear mass, normal front trail, wheelbase and distance between front centre of mass and rear centre of mass for the sports motorcycle and scooter.

The numerical model can be used to simulate various alterations in the parameters of the motorcycle that affect the dynamic behaviour such as the tyre pressure, effect of the steering damper of the sports motorcycle and tyre wear. A series of numerical root loci can therefore be generated comparing the standard vehicle with the modified configuration. An example is that of Figure 2 that shows the sports motorcycle in standard conditions and with low tyre pressures. These alterations can later be verified experimentally by conducting tests and identifying an experimental root locus.

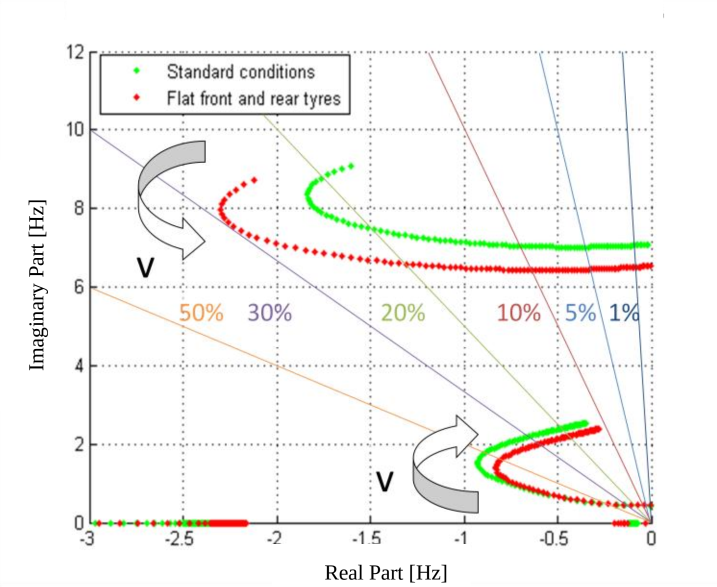

Figure 2 - Numerical root locus showing the sports motorcycle in standard conditions and with the front and rear tyres with low pressure. Iso-damping lines are also shown for various damping levels.

3 EXPERIMENTAL TESTS

Experimental tests have been carried out on a high performance sports motorcycle. Given the difficulty of exciting the vibration modes of this motorcycle during straight running, specific tests have been carried out at the Vairano Circuit Handling Track. In particular a steering pad has been executed at velocities from 20km/h to 60km/h with a 10km/h velocity step and a lane change executed at 30km/h and 50km/h has also been conducted.
Figure 3 shows the sensors used on board the sports motorcycle: steering sensor, front and rear linear potentiometers, an inertial platform and a proximitor. These sensors, in particular the

steering sensor and the lateral acceleration from the inertial platform, allow the study of the weave and wobble vibration modes via the offline diagnostic analysis interface (Figure 4).

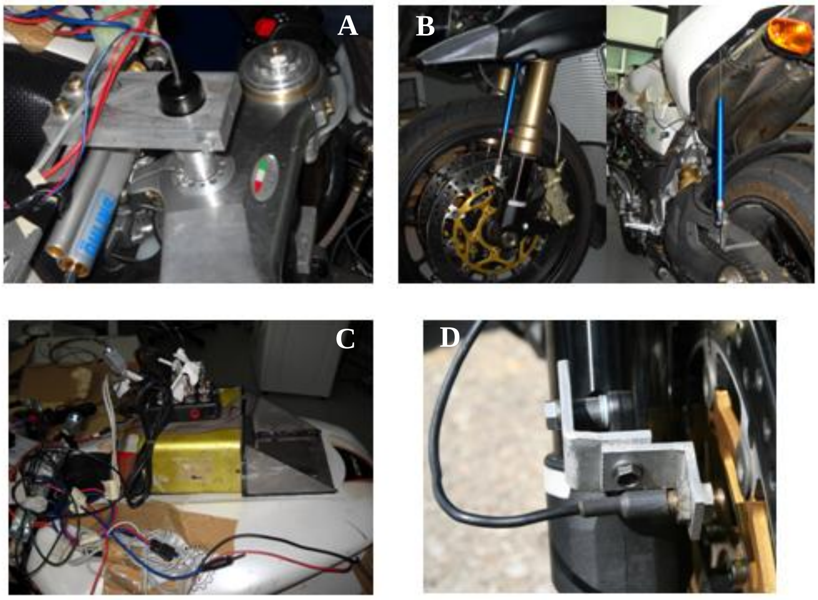

Figure 3 - Sensors used during the experimental tests: steering sensor (A), front and rear linear potentiometers (B), inertial platform (C) and a proximitor (D).

An example of the steering angle and the lateral acceleration time histories acquired during standard riding conditions during the steering pad conducted at 20-60 km/h with 10 km/h steps is shown in Figure 4.

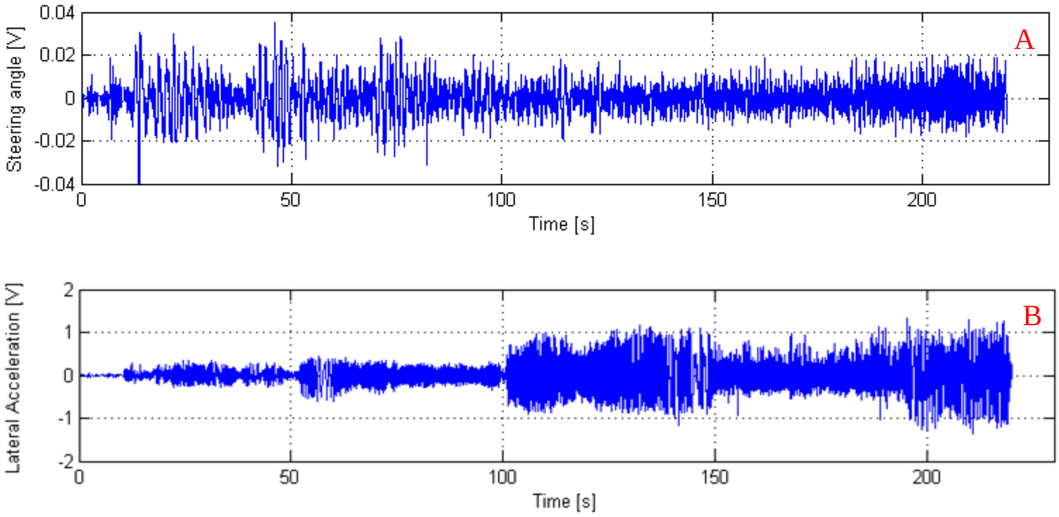

Figure 4 - Steering angle (A) and lateral acceleration (B) time histories from steering pad tests conducted on the sports motorcycle.

4 PROPOSED METHODOLOGY FOR INSTABILITY IDENTIFICATION

To identify when a mode of vibration becomes significant, and thus critical in terms of stability, the known frequency ranges for the weave and wobble vibration modes are used. A methodology has been developed with this precise aim, with the added objective of a final application in real-time. Figure 5 shows how a time history from the numerical model and an experimental time history can both be processed by the algorithm intelligence. The output is the frequency and damping of the weave and wobble vibration modes. This information can be given to the driver via the cockpit, be fed into a software for the analysis of the various vibration modes or be compared to a known numerical model for parameter tuning. In order to verify the efficiency and reliability of the methodology in identifying rapidly a variation in the frequencies and damping factors of the weave and wobble vibration modes a simulator of the algorithm logic has been created. The simulator receives as an input a numerical signal or an experimental signal, such as a steering angle or lateral acceleration time history, that is processed and the output is the frequency and damping factor of the vibration modes. This is compared to the input artificial signal parameters, known in the case of the numerical time history, in order to verify the performance of the methodology.

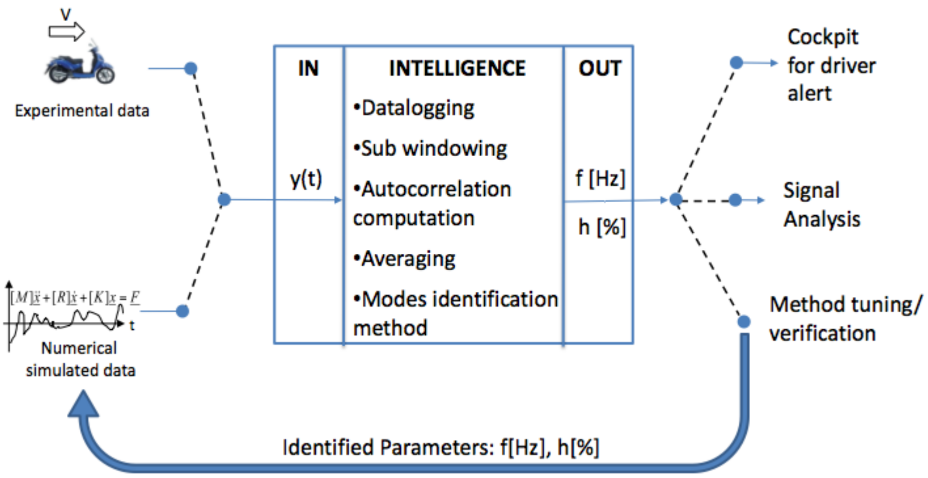

Figure 5 - The algorithm logic can process both numerical and experimental time histories and the outputs can be various based on the application.

The intelligence works begins by taking an input signal from the on-board sensors that are present and filters the incoming signal between 0.5 Hz and 12 Hz as the vibration modes are generally contained in this interval. The frequency range is chosen with a careful study of the literature available, which guarantees that the weave and wobble mode frequencies are included in this specific range ([4]). The sensors that are utilized are typically a steering angle sensor and an inertial platform that allows the measurement of the lateral acceleration. These two measurements are strictly necessary to be able to identify both the modes that are of interest. A pre-allocated matrix will arrange the filtered time signal in ten 5 second subwindows of time history with an overlap time of 0.1 seconds from one block to the other. The first iteration of the algorithm logic considers eleven blocks of 5 s time history. The time history has been chosen 5 s long in order to guarantee a frequency resolution of 0.2 Hz while taking into account the fact that the algorithm, having real-time ambitions, must provide the user with information efficiently and therefore a shorter time window allows for more rapid calculations. The choice of ten time windows with a time step of 0.1 s means that the user will have an update of the stability situation of the two-wheeled vehicle every second.

Having collected ten 5 s time histories, the logic is to generate the unbiased autocorrelation function for each of these and then compute the average autocorrelation function. This function is therefore a single averaged time history, ideally a decay function, which contains the frequency and damping information necessary to identify whether a vibration mode is being excited. The autospectrum function can also be evaluated which allows both time and frequency domain identification methods to be used for this purpose. Figure 6 shows an example of the application of the logic to the steering signal of a scooter during wobble mode manifestation. The 6-seconds time history is divided into ten 5-second subwindows and the autocorrelation function is computed for each of these windows. The average autocorrelation function is therefore calculated.

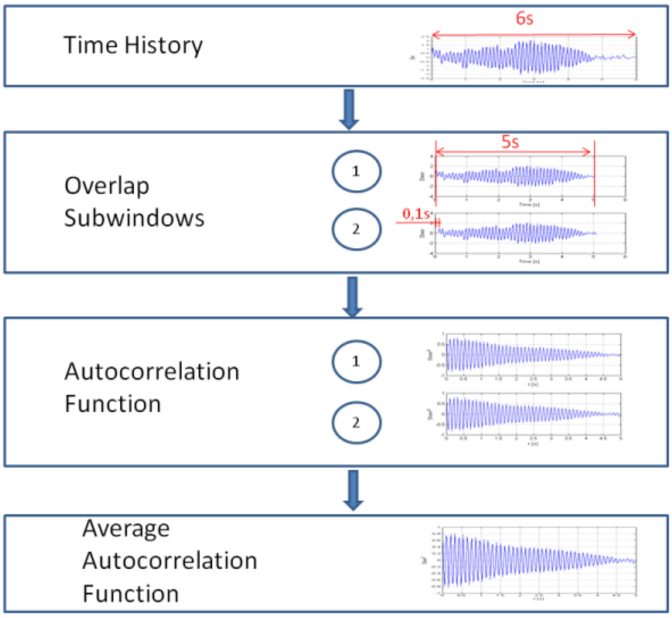

Figure 6 - Application of proposed methodology to the steering angle time history of a scooter during wobble mode manifestation.

The next step is that of choosing the most adequate mode identification method of the frequencies and damping factors of the weave and wobble vibration modes.

4.1 Analysed Mode Identification Methods

Five different methods, based in the time and frequency domains, for identifying the frequencies and damping present in the input signals have been studied. The methods investigated are:

- Logarithmic Decrement Method [12];
- Half-Power Bandwidth Method [12];
- Fitting Through A One Degree Of Freedom Frequency Response Function [12];
- Phase Differentiation Method [12];
- Prony's Method [13];

Firstly, to evaluate the various methods on a clean signal, a time history has been extracted from the numerical motorcycle model of the scooter in standard conditions. Using the four degrees of freedom model, the equations of motion have been integrated using a Matlab/Simulink model ([13]), giving as the initial condition a movement along the lateral displacement. The response of the system will therefore contain the desired vibration modes. This time history allows a first very simple application of the analysed methods with the aim of understanding initial weaknesses or strengths that may be present in the various investigation methods. The identification methods have also been applied on an experimental time history extracted from the scooter during straight running which shows a sustained wobble mode manifestation.

4.2 Methods Comparison

This section shows the various results obtained by the identification methods discussed in the previous section. Figure 7 shows the root locus with the point at 70 km/h that marks the weave and wobble vibration mode frequencies and adimensional damping coefficients.

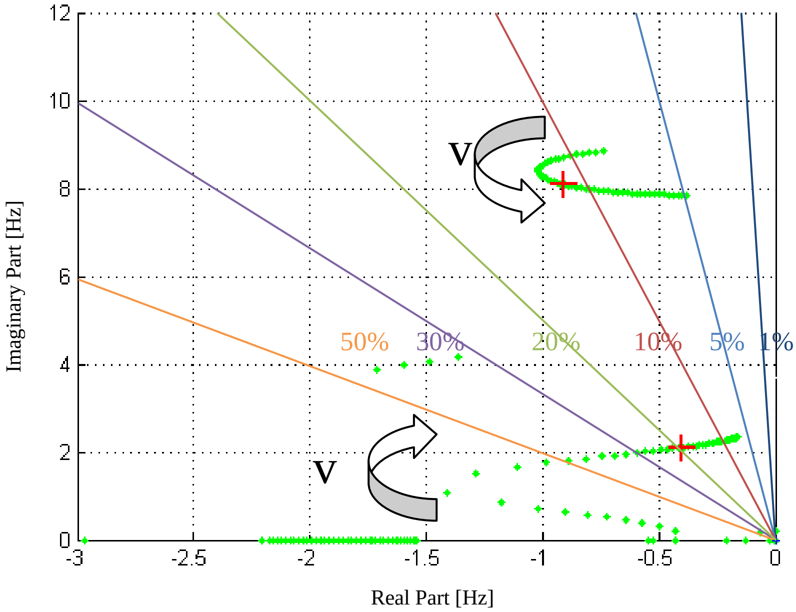

Figure 7 - Root locus showing the frequency and damping values of the weave and wobble vibration modes contained in the numerical time history. Iso-damping lines are also shown for various damping levels.

Table II shows the results obtained from the application of the different methods to this time history generated using the numerical model.

Method	*f* weave mode [Hz]	Error *f* weave mode [%]	*h* weave mode [%]	Error *h* weave mode [%]	*f* wobble mode [Hz]	Error *f* wobble mode [%]	*h* wobble mode [%]	Error *h* wobble mode [%]
Numerical	***2.1***	***-***	***19***	***-***	***8.1***	***-***	***11.2***	***-***
Logarithmic decrement	2.1	0	21.6	13	8.0	-1	10.8	-4
Half-power bandwidth	2.2	5	19.8	4	8.2	1	11.4	2
Fitting through a one DoF FRF	2.5	19	27	42	8.2	1	6.8	-39
Phase differentiation	2.2	5	23.9	26	8.2	1	9.5	-15
Prony	2.1	0	17.7	-10	8.2	1	10.8	-3

Table II - Frequency f [Hz] and adimensional damping factor $h=r/r_c$ [%] for the standard scooter vehicle: input data is a numerical simulation at 70 km/h. A comparison between the identified frequency and damping values of the weave and wobble vibration modes using different identification methods and the numerical input is conducted.

By observing Table II it is possible to notice that each method is able to identify, more or less accurately, the weave and wobble vibration mode frequencies starting from the numerical time history, while the damping factor is better obtained by the Prony's method, the logarithmic dec-

rement method and the half-power bandwidth method for both the weave and wobble vibration modes.
The methodology has also been applied to an experimental time history (Figure 8) in order to verify which of the identification methods is most effective. In particular a steering angle acquisition from the scooter has been used. Table III shows that the wobble frequency found by the methods that work in the frequency domain is the same, as expected, as each of them starts from the same spectrum of the time history. The damping factor varies in a very limited interval, but since the logarithmic decrement method, the fitting through a one degree frequency response function and Prony's method find approximately the same result, this is assumed to be the most plausible.

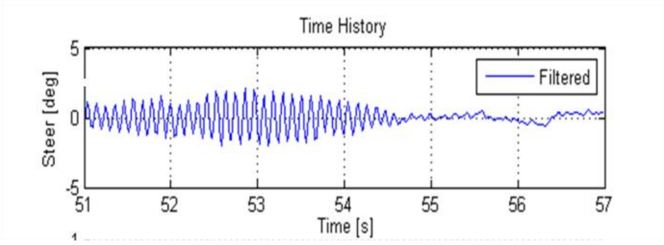

Figure 8 - Filtered experimental time history of the steering sensor mounted on the scooter during standard riding conditions.

Method	*f* [Hz]	*h* [%]
Logarithmic decrement	9.25	1.2
Half-power bandwidth	9.4	1.8
Fitting of a 1 dof FRF	9.3	1.4
Phase differentiation	9.4	2.1
Prony	9.4	1.3

Table III - Comparison of the results obtained from different identification methods applied to the experimental time history.

Therefore, comparing the different results obtained for both the numerical and experimental time history, Prony's method shows the best performance as it is more accurate than the other methods and allows the identification of various vibration modes simultaneously. It is also not particularly complex to implement in automatic in the algorithm logic. In order to succumb to the only real defect of Prony's method, which is the limited time efficiency, the half-power bandwidth method has also been chosen to be used in the algorithm logic for a macro estimate of the damping factor before Prony's method is executed.

4.3 Chosen Methodology

The methodology has been integrated into an offline diagnostic analysis interface that processes an input experimental time history from the scooter and, after being processed, returns a complete analysis regarding the vibration modes. Figure 9 shows the user interface that has been developed for the analysis of the vibration modes.

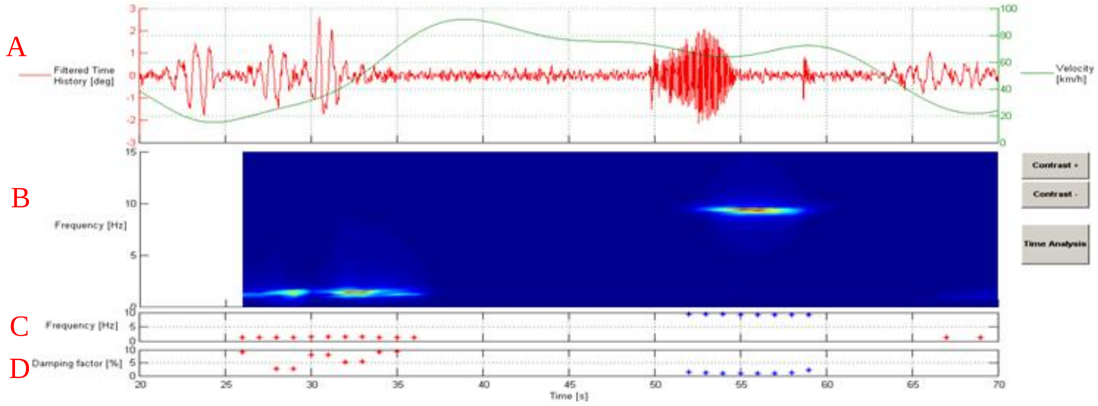

Figure 9 - The user interface: filtered steering angle time history from scooter during generic running. From top to bottom: (A) time history acquired by sensor and vehicle speed, (B) spectrogram, (C) identified frequencies, (D) identified damping coefficient.

In section (A) of Figure 4 the acquired time history from the steering sensor of the scooter and the vehicle speed is shown. In section (B), a 3D plot of the spectrum of the averaged autocorrelation function at various time intervals where the color map represents the amplitude level is shown. A low damped weave manifestation and low damped wobble identification can both be identified Section (C) illustrates the frequencies identified by Prony's Method (red for the weave mode and blue for the wobble mode), while in box D the corresponding damping factors are shown. The figure also shows that at t=57 seconds there is sustained wobble oscillation. The spectrogram identifies a high amplitude (in red), while Prony's method identifies a fairly constant frequency and a decreasing damping coefficient as the oscillation enters the algorithm's observation window.
The use of this interface therefore presents the user with information relative to the frequencies and damping factors identified on the entire time signal analysed and a specific function, noted as "Time Analysis" in Figure 9, has been added in order to allow the user to analyse a result presented in the offline analysis results window at a specific time instant.

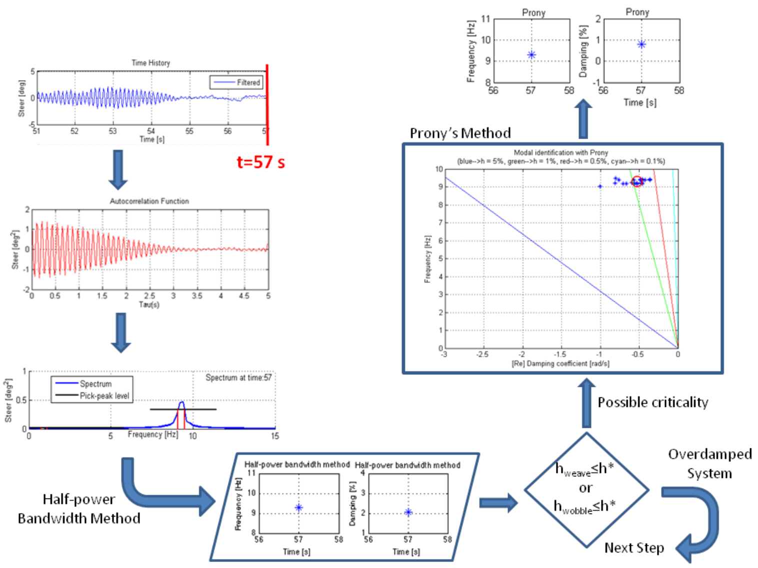

Figure 10 - Flow chart showing the logical procedure of the algorithm logic.

Figure 10 shows how starting from the time history the average autocorrelation function is calculated. The methodology follows by employing the half-power bandwidth method on the spectrum of this function. This identification method is employed twice: once for frequencies from 0.5 to 6 Hz, aiming to investigate possible manifestation of the weave vibration mode and exclude possible manoeuvres from the spectrum, and once for frequencies from 6 to 12 Hz to check the wobble vibration mode. This results in a complete analysis of the passband after the filter operation. If one of the two applications of the half-power bandwidth method finds a damping factor lower than a pre-set value (h*), Prony's method is launched on the averaged autocorrelation function. If the damping factor of both vibration modes is higher than the pre-set value the algorithm conducts no further analysis of the specific time window and the algorithm procedure restarts. The threshold under which Prony’s method is not used is decided considering that above that threshold a mode manifestation is not dangerous for rider's safety as it is significantly damped and can therefore be disregarded. The pre-set value is typically not universal and must be set depending on the type of vehicle used. Experimental tests conducted on the vehicle can be used to tune this parameter.

The choice of using this two-stage identification process is made to avoid that Prony's method processes all the signals, even if there is no mode manifestation: this would lead to a slow algorithm that analyses the experimental data when it is unnecessary. One of the main difficulties regarding Prony’s method is relative to the choice of the number of harmonics (poles) on which the method tries to match the decay function. The choice of the number of poles is therefore a compromise between calculation rapidity (low number of harmonics) and allowing Prony’s method to identify all of the significant harmonics present. In this work a chosen range of 5-15 poles has been chosen based on the application of the Final Prediction Error (FPE), Akaike Information Criterion (AIC) and Minimum Description Length (MDL) criteria which has allowed the determination of an optimum harmonic range for the algorithm logic.

5 ALTERATIONS AND RESULTS

The tests on the sports motorcycle have all been conducted by a professional rider and the variations conducted on the motorcycle are listed in Table IV. At the lower velocity runs, 20km/h, 30km/h and 40km/h, the motorcycle does not have a large camber angle (the motorcycle is nearly upright in fact) and therefore a comparison with the numerical model valid in straight running is acceptable. At the higher velocity runs (50km/h and 60km/h), due to the motorcycle being more leaned over, there can be a coupling of the in-plane and out-of-plane modes. A bibliographic research shows that the weave mode for example may be less damped in these conditions respect to straight running as there is a coupling with the bounce mode, however this is heavily dependent on the running conditions ([3]). The wobble mode instead may couple with some suspension movements ([3]) that may cause a slight frequency increase, however if the lean angle is not excessive the wobble mode is not particularly affected ([4]). These considerations lead to believe that some differences are no doubt present between the experimental root locus and the numerical root locus, however an initial sensitivity analysis can no doubt be effectuated.

	Steering damper	Front tyre pressure [bar]	Rear tyre pressure [bar]	Front suspension	Rear suspension
STD	Min	2.5	2.5	original	original
Config. 1	Min	1.5	2.5	original	original
Config. 2	Min	1.5	1.5	original	original
Config. 3	Max	2.5	2.5	original	original
Config. 4	Min	2.5	2.5	low	low
Config. 5	Min	2.5	2.5	high	high

Table IV - Vehicle configurations for the sports motorcycle in the tests conducted. The first configuration is the standard setup and in addition to this six additional configurations were tested.

Tests previously conducted on a typical 250cc scooter during straight running, where impulses are applied on the steering assembly at 70 km/h, 100 km/h and 120 km/h, are also analysed and in particular the following vehicle configurations have been analysed:

- standard conditions;
- reduced front trail;
- without steering balance;
- with rear load;
- with weared tyres;

Figure 11 shows a comparison between the numerical root locus of the sports motorcycle respectively in standard conditions and with a lower front and rear tyre pressure (1.5 bar each). To take account of this change on the numerical model, the roll and slip stiffness of the front and rear tyres have been reduced by 10% and the relaxation lengths have been increased by 10%. A tyre manufacturer has also confirmed these variations.

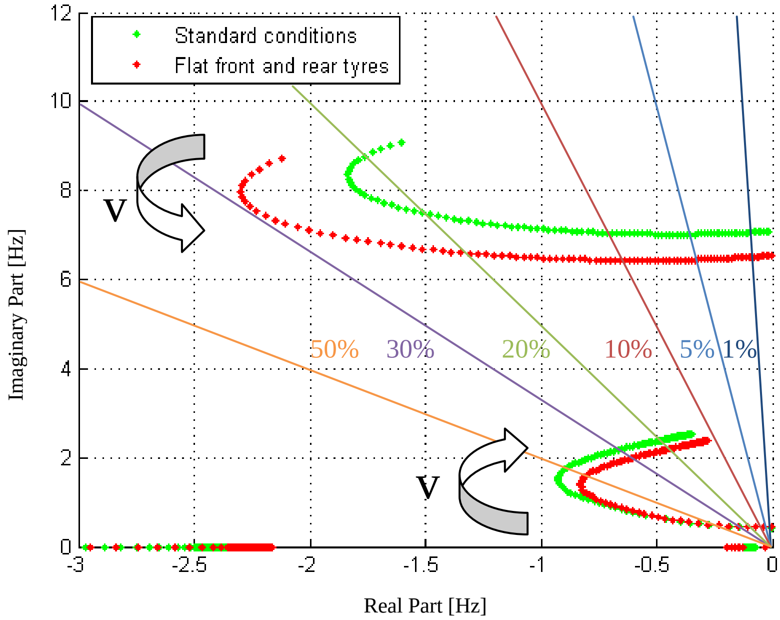

Figure 11 - Comparison between the root loci of the sport motorcycle in standard conditions (green) and with flat front and rear tyre (red) in a speed range of 20-120 km/h. Iso-damping lines are also shown for various damping levels.

Figure 12 presents a numerical-experimental comparison between the sports motorcycle in standard conditions and with a lower front and rear tyre pressure. Figure 12 (a) shows that for the wobble vibration mode at 20km/h the results are coherent with the numerical model but slightly less damped, at high velocities the experimental data differs in that it presents an even lower damping factor than that of the four degree of freedom model. The weave vibration mode on the other hand presents a decent fitting for the whole range of velocities studied. At lower velocities there seems to be a greater accordance for this mode, whilst at higher velocities the mode seems to be less damped. Figure 12 (b) also shows that in the weave zone there is accordance between the experimental results and the numerical results, while in wobble zone the experimental results are harder to interpret. In particular at 20km/h the experimental data show a much lower frequency and higher damping than that of the numerical model, while at 60km/h there is a slight increase in frequency while the damping is coherent with the mathematical model.

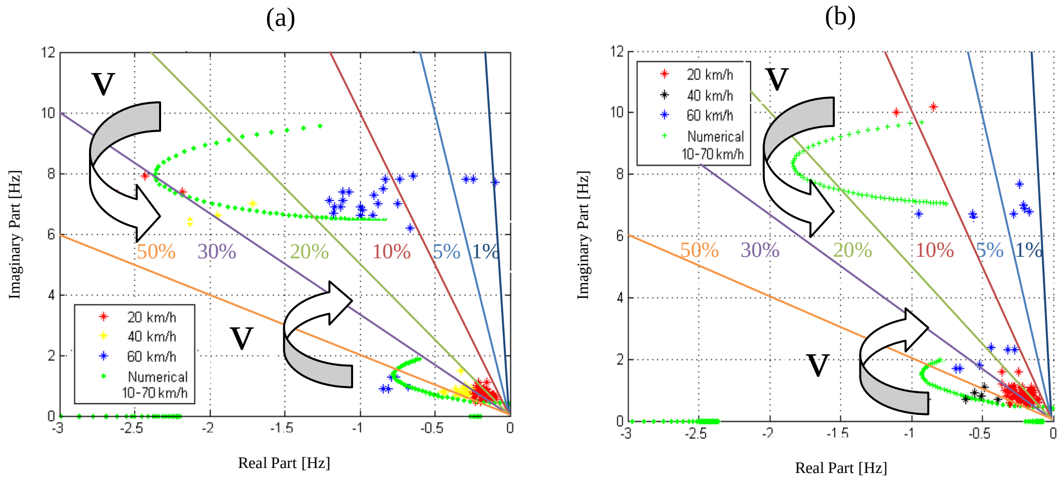

Figure 12 - (a) Comparison between the results of the numerical model and the experimental results of the sports motorbike in standard conditions. (**b)** Comparison between the results of the numerical model and the experimental results of the sports motorbike with flat front and rear tyre. Iso-damping lines are also shown for various damping levels.

Figure 13 shows the numerical comparison between the root locus of the scooter in standard conditions and without the use of steering balances. In the numerical model this aspect has resulted in the changes of the front mass and of the inertia moment around the steering axis. In the case of not installing the steering balance, the first parameter has been decreased of 0,5 kg, while the second, supposing that the steering balance position was distance 0,3 m from the steering axis, was decreased of 0,09 kgm^2. It is possible to notice that the vehicle with the steering balances has lower wobble frequencies and higher damping and this is in accordance with the physical problem: an increment of mass causes a decrement of the frequencies, by the definition of natural frequency. The weave vibration mode does not present an important modification as the two curves are very similar, both in frequency and in damping.

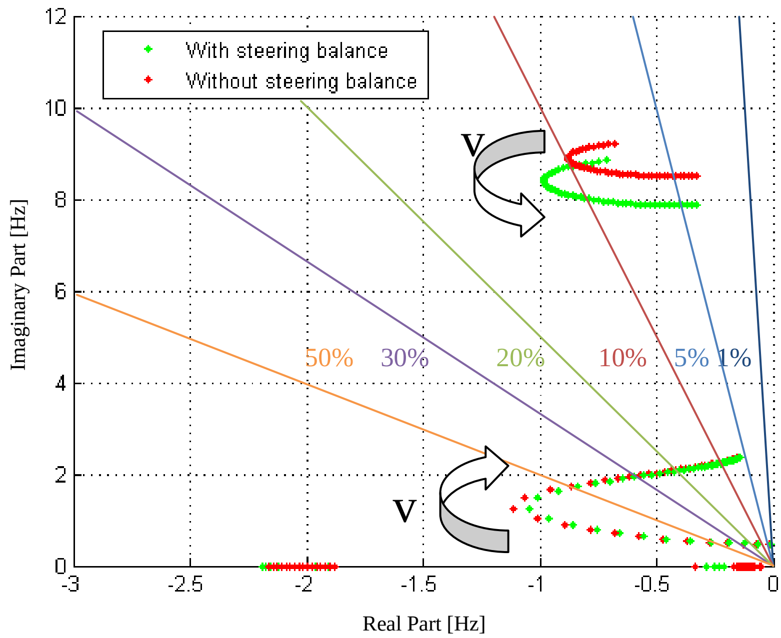

Figure 13 - Numerical comparison between the root loci of the scooter with increased front trail, with the steering balances (green) and without the steering balances (red) in a speed range of 20-120 km/h. Iso-damping lines are also shown for various damping levels.

Figure 14 shows the numerical-experimental comparison between the scooter in standard conditions and without the use of steering balances. The experimental root loci are extracted using the proposed methodology and the numerical root loci are extracted from the numerical model shown in Section 2. Unfortunately not all the velocity runs were able to give substantial results and so only the significant points are plotted. This problem could be resolved by laying down a series of wooden bumps in order to excite the vehicle with a frequency sweep with a greater energy introduction, as explained in [4].

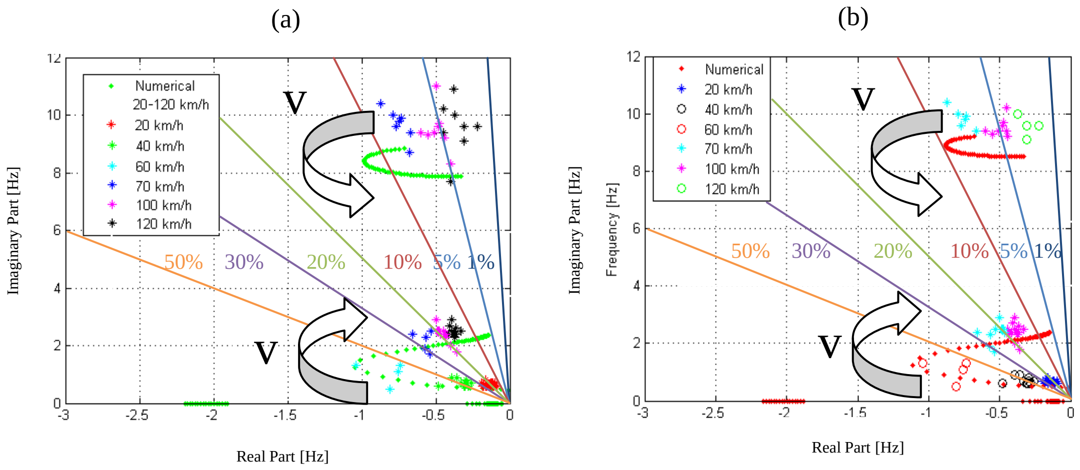

Figure 14 - (a) Comparison between the numerical model and the experimental results of the scooter in standard conditions with speed interval 20-120km/h. (**b)** Comparison between the numerical model and the experimental results of the scooter without the use of steering balances with speed interval 20-120km/h. Iso-damping lines are also shown for various damping levels.

Figure 14 (a) presents a weave vibration mode with frequencies and alpha values for the various velocities very similar between the experimental and numerical results, while in the wobble region the natural frequencies are slightly higher than those obtained with the numerical model even though the velocity trend is respected. This fact could be due to differing testing conditions than those replicated by the numerical model or a slight change of the vehicle used during the tests that may have provoked this effect, however these hypothesis are not verifiable. In Figure 14 (b) it is possible to notice that the weave vibration mode presents a good fitting and follows the velocity trend quite accurately while the wobble vibration mode, as in the previous test, shows a higher frequency for the experimental data than that of the numerical model and therefore presents a lower damping factor for the various velocities.

6 METHODOLOGY IMPLEMENTED FOR REAL-TIME APPLICATION

To emulate a real-time application the algorithm logic no longer loads the whole the pre-acquired signal from the desired sensor but loads one point at a time from that specific signal. A buffer where the time window required for the analysis is stored is therefore used before the data is processed. As the time history develops the information from the sensors and the results of the analysis are stored. Since the methodology is being implemented in order to detect an incurring instability of the vehicle, a certain number of checks have been integrated into the various phases of the algorithm logic. In particular, limits have been pre-set with regards to the damping factor calculated by the algorithm. The idea is to allow a faster and more effective analysis to be conducted, crucial when referring to an on-board system that must run in real-time conditions. Limits have been set on the two control points of the methodology, in particular when the Half-power bandwidth method and Prony's method are applied. Regarding this first identification method, if the two damping factors for the weave and wobble vibration modes, or one of the damping factors, is below a pre-set value then the analysis continues, otherwise no further analysis is done on that time window. To determine the pre-set value, specific tests must

be undertaken to tune this parameter as different types of vehicles behave in different ways. If the analysis continues, and therefore Prony's method is launched, the result of the analysis is filtered through another set of critical damping factor levels, which determines the information that is effectively given to the driver.
The easiest way to transmit the information from the algorithm logic to the driver is through the dashboard. The information presented must be limited as the rider must not be distracted from normal operation during the use of the two-wheeled vehicle. As is most intuitive the information has been transmitted to the driver using an instability indicator in the form of a set of progressive lights that indicate how the motorcycle is behaving (more information on human machine interaction can be found in [14]).
A GUI (Graphical User Interface) has been developed to show the applicability of the proposed methodology to a real-time ADAS system. The input is an experimental time history, while the output is the frequency and damping of the identified vibration modes and an instability indicator for the driver. Figure 10 shows the emulator user interface:

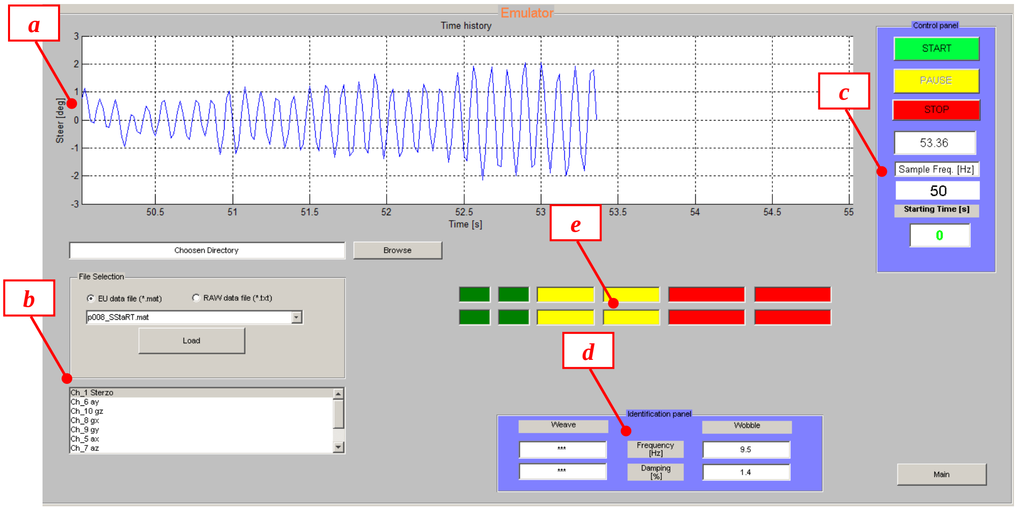

Figure 10 - GUI (Graphical User Interface) used to emulate real-time application of the algorithm logic: Time history (a), data load (b), control panel (c), identification panel (d) and instability indicator (e).

The damping factor boundaries that have been set for the instability indicator, and therefore define whether a green, yellow or red light are shown to the driver, are based on the limits that define the region between a "safe" situation and a "dangerous" situation. These boundaries are clearly subject to variation based on the type of vehicle and the use that the vehicle has been designed for.
Through extended use of the emulator it has been noticed that the plotting of the various figures present causes a delay of the algorithm. This is due to the continuous plotting and holding of data points on screen that requires a heavy computational burden. In order to test the real-time capabilities of the algorithm logic more realistically and determine the time efficiency, the algorithm has been tested without the continuous plotting of the time history but only using the instability indicator as would happen with an on board implementation. In this situation the methodology is able to run adequately fast for a real-time use as in a defined time interval the algorithm has already analysed roughly three times this time period. This value is an average based on various computers tested with differing processors, however specifically the time efficiency clearly depends on the computational performance of the computer used for the analysis.
Another important factor regards the sample frequency used by the data acquisition system, as an excessive sample frequency is not only unnecessary due to the frequency interval in which the vibration modes of interest are found but also slows down the algorithm logic significantly.

7 CONCLUSIONS

A methodology for the identification of instability phenomena that may occur on generic two-wheeled vehicles in motion has been presented. In order to fulfil these criteria a specific algorithm logic has been developed with two fundamental uses: offline diagnostic system useful during the design stages of a generic motorcycle to analyse and evaluate experimental data and a real-time ADAS (Advanced Driver Assistance System) able to identify a dynamic instability of a generic two-wheeled vehicle in generic driving conditions. Various tests have been conducted on a sports motorcycle in order to test the effectiveness of the methodology. The results of the sensitivity analysis on a sports motorcycle and a scooter have been presented, highlighting a good accordance between the experimental root loci and the numerical root loci for the weave mode, while the wobble mode is seen to be harder to observe experimentally. The proposed methodology has been implemented in an emulation of a real-time context using a GUI (Graphical User Interface) and the time efficiency and effectiveness of the instability monitoring has been verified. Logically the next step is that of the implementation of the methodology in real-time on board a two-wheeled vehicle by compiling the software on an ECU (Electronic Control Unit). The future applications of the algorithm logic are related to an integration of the methodology with an active control system in order to directly act on the vehicle when a possible instability is identified.

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