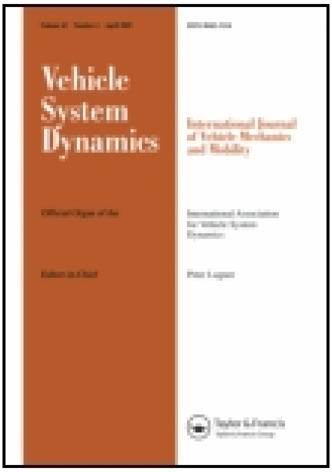

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Analysis of racing motorcycle performance with additional considerations for the Mozzi axis

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Analysis of racing motorcycle performance with additional considerations for the Mozzi axis

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The aim of this research is to develop techniques for the analysis of data measured in motorcycle races. This analysis should highlight the most difficult parts of the circuits, the rider's skill and effort, the performance of the vehicle and the achievement of limit conditions for the vehicle and the tyres. Several analysis techniques are presented and applied to manoeuvres carried out by different motorcycles both on dry and wet tracks. Interesting results are obtained with a method based on the time rate of the kinetic energy of orientation, and a criterion for identifying the most exacting phases of the manoeuvre is proposed.

Keywords: motorcycle; racing; road test; screw axis

1. Introduction

In race tracks, two-wheeled vehicles reach astonishing performances with large accelerations, large velocities and roll angles up to 60°. Experimental data dealing with racing motorcycles are very useful both for understanding motorcycle dynamics and riding techniques and for validating dynamic simulation codes. Unfortunately, very few experimental data are available in the literature, because the measurement of the relevant dynamic quantities is difficult and requires expensive equipment and because racing teams seldom publish their confidential data.

This paper deals with the analysis and elaboration of experimental data collected in the framework of two research projects. The first project was carried out by the University of Padova and Dainese and was aimed to develop more protective motorcycle garments [1,2].

The second project was carried out by Padova University and was aimed to study the chattering of racing motorcycles [3].

Experimental data were collected with the equipment developed by 2D-data recording GmbH Germany. In particular, angular velocities were measured with gyrometers, accelerations with accelerometers and the trajectory of the motorcycle with high-frequency GPS.

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In order to highlight the influence of the characteristics of the motorcycle on the riding style, two very different racing vehicles (a 125 cc and a superbike (SBK)) running on the same race track are considered. To show the influence of the environmental conditions on the performance and riding style, data collected on dry and wet tracks are presented as well.

In the first section of the paper, the most relevant dynamic parameters measured in many laps are presented and discussed: they are the lateral and longitudinal accelerations (thrusting or braking), roll and yaw rates.

A lap can be considered as composed of some quasi-stationary phases (e.g. accelerated or decelerated rectilinear motion, turning at nearly constant speed) jointed by transient phases (e.g. entering and exiting a curve, chicane curve). On the one hand, the transient phases are the most complex and interesting, because they are strongly influenced by the riding strategy and by the dynamic characteristics of the two-wheeled vehicle. On the other hand, the quasi-stationary phases are mainly influenced by the particular abilities of the rider (e.g. the ability of perceiving the road grip in acceleration) and by some properties of the vehicle (e.g. engine characteristics and tire longitudinal grip in acceleration). There is another important theoretical difference between the different phases of the motion along a race track. In the quasi-stationary phases, the roll rate is nearly zero, whereas the yaw rate is nearly constant (steady turning) or nearly zero (rectilinear motion). In the transient phases, there is a complex combination of roll and yaw rates, which depends on the dynamic properties of the vehicle and on the riding style.

The second section of the paper deals with the analysis of transient manoeuvres performed both with dry and wet track. To highlight the differences in riding style, some calculations are carried out with the Mozzi axis approach. This method proved to be useful for analysing transient manoeuvres with a general combination of roll and yaw rates [4,5].

Finally, a quantitative index depending on the time derivative of the kinetic energy of orientation is presented. It is useful for highlighting the most exacting parts of the circuit, in which the lateral dynamics of the motorcycle may reach a limit condition and a large mental/physical effort is requested from the rider.

2. Racing motorcycles experimental data

The distribution of the velocities reached by a motorcycle in the different parts of a race track is interesting, but it gives only qualitative information and does not highlight if the rider has reached the limit values of motorcycle performance and tyre adherence.

The performance of a motorcycle and the rider's capability of exploiting the vehicle can be better assessed by analysing the distribution of longitudinal and lateral accelerations. The longitudinal accelerations depend on the available engine torque, maximum longitudinal force coefficient of the tyres, mass distribution of the vehicle and braking system characteristics. The lateral accelerations are related to the roll angle and are intrinsically limited by the maximum normalised lateral force of the tyres (the ratio between the lateral tyre force and the vertical load). The combination of these two accelerations is related to the area of the friction ellipse of the tyres [6] used by the rider: the wider the area the higher the ability of the rider to exploit the engine and tyre performances.

Figure 1 deals with a 125 cc racing motorcycle ridden by a professional rider in a world championship circuit (Le Mans) and shows the distribution of lateral and longitudinal accelerations measured in 10 laps.

The experimental points do not cluster on the axes of abscissas and ordinates (pure cornering and pure braking/thrusting, respectively), and this characteristic is an index of the rider's skill of braking and thrusting in cornering. The distribution is nearly symmetric in

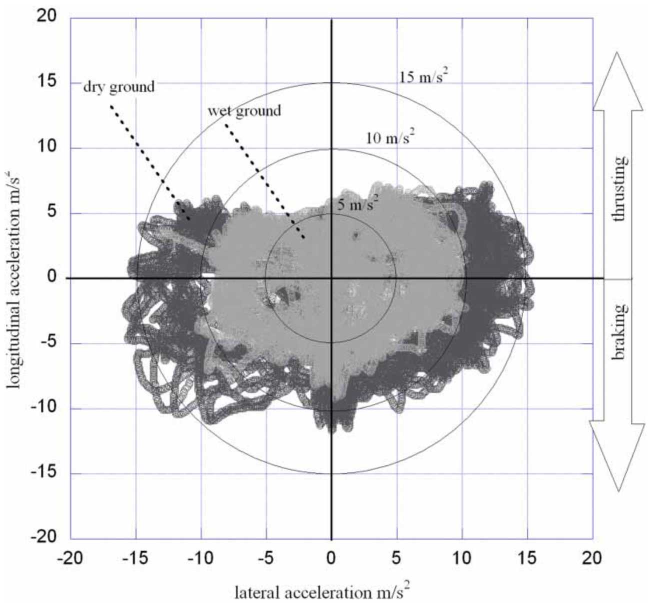

Figure 1. Distribution of accelerations, 125 cc motorcycle in dry and wet conditions.

the lateral direction and non-symmetric in the longitudinal direction. The largest values of acceleration (about $15\,\mathrm{m/s^2}$) are reached when the acceleration is only lateral (cornering) or when it is a combination of a large lateral acceleration and a smaller longitudinal acceleration (braking/thrusting in cornering).

A clear phenomenon is the limit of the longitudinal thrusting acceleration (about $6\,\mathrm{m/s^2}$), which is related to the maximum torque delivered by the engine. The maximum braking acceleration is smaller (in modulus) than the maximum lateral acceleration.

The inertia forces of the whole vehicle are proportional to accelerations, the proportion coefficient being mass m. The total gravity force is mg, where g is the modulus of gravitational acceleration. The longitudinal/lateral inertia forces are balanced by the longitudinal/lateral tyre forces, and the gravity force is balanced by the tyre vertical loads. Therefore, the ratio between the accelerations and g is the ratio between the longitudinal/lateral tyre forces and tyre's vertical loads.

Figure 1 shows that in pure cornering, the ratio between the maximum lateral acceleration and g is about 1.5; this value corresponds to a large normalised lateral force generated by the tyres that are fully exploited by the rider. In braking, the ratio between longitudinal acceleration and g is about 1.1, which represents a good exploitation of tyre adherence.

In Figure 1, a second distribution of experimental points is presented (light grey spots). It refers to the same motorcycle ridden by the same rider on the same race track but with the track made wet.

The comparison between the two distributions of points (dry/wet) highlights the relationship between accelerations and tyre performances. On the wet track, a large reduction appears in the lateral acceleration: the maximum values are about $10\,\mathrm{m/s^2}$ ($15\,\mathrm{m/s^2}$ with dry road). The longitudinal accelerations in braking decrease (maximum value about $8\,\mathrm{m/s^2}$) but not as much as lateral accelerations do. No significant variation in the longitudinal acceleration in thrusting appears; this means that the most stringent limit is still the engine torque. Globally, the distribution of experimental points is more symmetric.

Therefore, the wet track limits the performance of the vehicle especially when relevant lateral tyre forces are required. This phenomenon is a consequence of a large reduction in the maximum lateral force coefficient of the tyres and may be related to a rider's feeling – one who adopts a more conservative riding style in cornering.

The diagram presented in this section is useful also for comparing the performances of different vehicles running on the same race track. Figure 2 refers to Mugello circuit (10 laps)

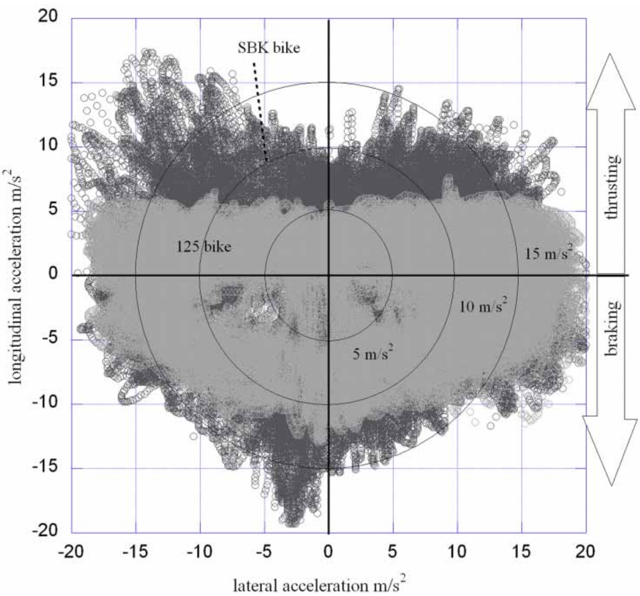

Figure 2. Distribution of accelerations, superbike and 125 cc in dry condition.

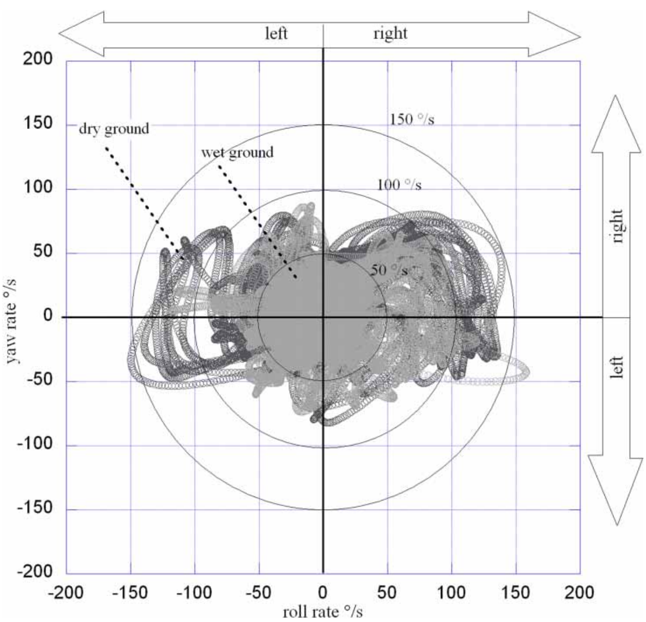

Figure 3. Distributions of the components of angular velocity, 125 cc motorcycle.

and compares the performances of a 125 and an SBK in terms of acceleration. The track was dry during the tests.

Both the 125 cc (light grey spots) and the SBK (black spots) reach the same lateral accelerations (19 m/s^2), but the SBK shows larger accelerations in thrusting and in thrusting when cornering. This effect is clearly related to the larger torque of the SBK engine. In braking when cornering, the two vehicles show similar accelerations. The maximum acceleration in braking is larger for the SBK and can be related to the higher speed of this vehicle.

The distribution of roll rate $\dot{\varphi}$ and yaw rate $\dot{\psi}$ is another useful tool to analyse the performance of the motorcycle and the rider's ability and style. The roll and yaw rates are the most important components of the angular velocity, since the pitch rate is usually smaller. The yaw rate is the most important component of angular velocity when the vehicle is turning at nearly constant speed, whereas the roll rate is large in transient manoeuvres.

Figure 3 refers to the same motorcycle, rider and circuit as Figure 1. Experimental data measured in 10 laps are represented. If the track is dry, roll rate $\dot{\varphi}$ reaches the largest values. Roll and yaw rates are also large when both components of the angular velocity are present (points near the diagonals). When the track is wet, the extension of the cluster of points decreases, and there are large decrements in the maximum values of roll rate $\dot{\varphi}$.

3. Analysis of transient manoeuvres

3.1. *Kinematics of transient manoeuvres*

A typical manoeuvre with important transient phases is the U-turn manoeuvre. Figure 4 deals with this manoeuvre and shows the paths of a 125 cc motorcycle measured on dry and wet tracks.

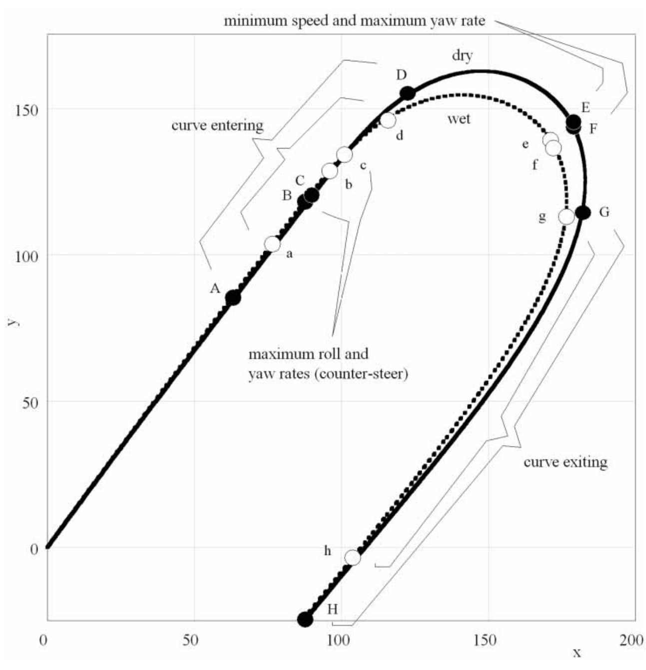

Figure 4. Paths in U-turn manoeuvres (125 cc motorcycle).

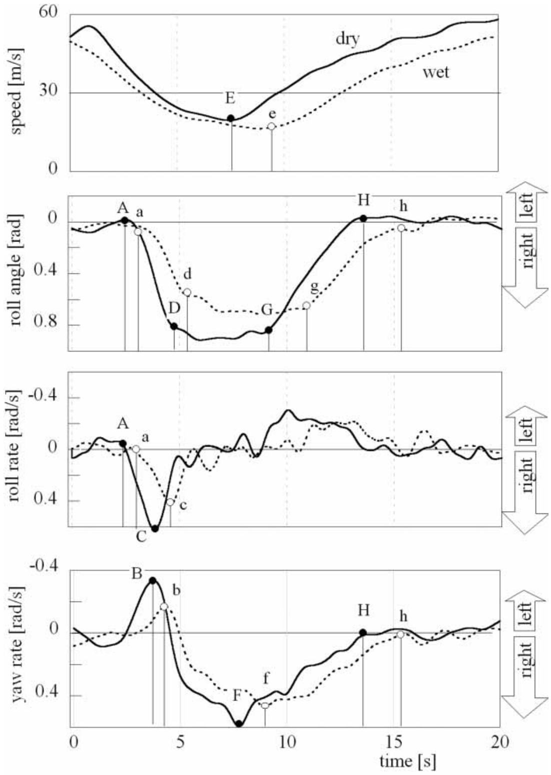

Figure 5. Linear velocities, roll angles and angular velocities in U-turn manoeuvres (125 cc motorcycle).

In order to highlight the characteristics of the motion of the motorcycle, some typical points are considered:

- interval A–D corresponds to curve entering,
- interval D–G corresponds to a rough steady turning,
- interval G–H corresponds to curve exiting.

The points marked with lower case letters correspond to the path traced on wet ground.

The most important difference that appears when the track is wet is a reduction in the radius of curvature of the quasi-stationary part of the U-turn manoeuvre. On wet ground, the entering and exiting phases are performed in a shorter distance (but in time domain, the intervals are almost the same since the speed is smaller, see Figure 5). Actually the path of the motorcycle depends on road grip and engine power: a decreased road grip leads to a shorter radius of curvature.

Figure 5 shows some important kinematic quantities of the U-turn manoeuvre carried out on dry and wet track: speed, roll angle, roll and yaw rate. The quantities that are very sensitive to the condition of the track may be considered closely related to the dynamic limits of the manoeuvre.

Point A is the beginning of the manoeuvre, and it is characterised by a sharp increase in the roll rate. The rider adopts a counter-steer technique to enter the curve, and point B corresponds to the maximum value of the yaw rate in the counter-steer phase (maximum yaw rate towards left in a right curve). Point C is very close to point B and corresponds to the maximum roll rate.

After point D, the roll angle is less variable and its values are close to the maximum value, the quasi-stationary part of the curve begins. Point E corresponds to the minimum value of forward speed and is very close to point F, which corresponds to the maximum yaw rate towards the right.

In interval G–H, the motorcycle exits the curve. The roll rate does not reach the peak value typical of curve entering, but shows a flat top (lasting about 4 s). The yaw rate tends to zero with some oscillations.

A clear and foreseeable difference between the manoeuvres carried out on dry and wet tracks is a generalised reduction in the forward speed. Only in that part of the manoeuvre that follows the maximum peak of roll rate is the difference between the forward speeds small.

In consequence of the reduced forward speed, when the track is wet, the typical points (lower case letters) occur later in time than when the track is dry (capital letters). The comparison between roll angles shows that, if the track is wet, the rider adopts a smaller roll angle for a longer interval of time. Moreover he strongly limits the fast variation in the components of angular velocity, and relevant differences appear in the peaks of yaw rate in the counter-steer phase (the difference between points B and b is about 0.16 rad/s) and in the peaks of roll rate (the difference between points C and c is about 0.2 rad/s). Therefore, the quick variation in the components of angular velocity corresponds to a limit condition of lateral dynamics, which becomes more stringent when the ground is wet.

3.2. *Mozzi axis analysis of transient manoeuvres*

The Mozzi Theorem [7] states that the motion of a rigid body is represented in every instant by rotation about and translation along the Mozzi axis, which coincides with the instantaneous direction of the angular velocity vector. The Mozzi axis is also known as the instantaneous screw axis. Strictly speaking, a motorcycle is not a rigid body, owing to the steer rotation, the motion of the rider's body with respect to the vehicle and the presence of suspensions that permit the pitch motion. If the pitch and body motions are very small, the rear frame of the motorcycle (with the rider) can be considered to be a rigid body, and the Mozzi axis can be calculated in every instant.

The Mozzi axis is useful for describing certain aspects of transient manoeuvres. Figure 6 shows the Mozzi axis and the coordinate systems. In the fixed coordinate system axes, x_f and y_f lie on the track plane, and axis z_f is vertical and directed downwards. A mobile coordinate system is established at the contact point of the rear wheel of the motorcycle, axis x_s is horizontal and parallel to the symmetry plane of the vehicle, axis z_s vertical and directed downwards and axis y_s parallel to the road plane. The mobile coordinate system is not attached to the rear frame of the vehicle, because the vehicle rotates by roll angle φ about axis x_s. Yaw angle ψ is the angle from x_f to x_s.

The Mozzi axis moves in the space, and it can be described in two-dimensional plots by means of two parameters: the Mozzi angle and the Mozzi trace.

Mozzi angle θ is the inclination of the Mozzi axis with respect to the track plane [4]:

$$\theta = \arctan\left(\frac{\dot{\psi}}{\dot{\varphi}}\right). \tag{1}$$

The Mozzi trace is the intersection of the Mozzi axis with the track plane. If the rear sideslip is very small, the coordinates of the Mozzi trace in the mobile frame are

$$^{s}x_\mathrm{M} = 0, \quad ^{s}y_\mathrm{M} = \frac{\dot{\psi}\ V}{\dot{\psi}^2 + \dot{\varphi}^2}. \tag{2}$$

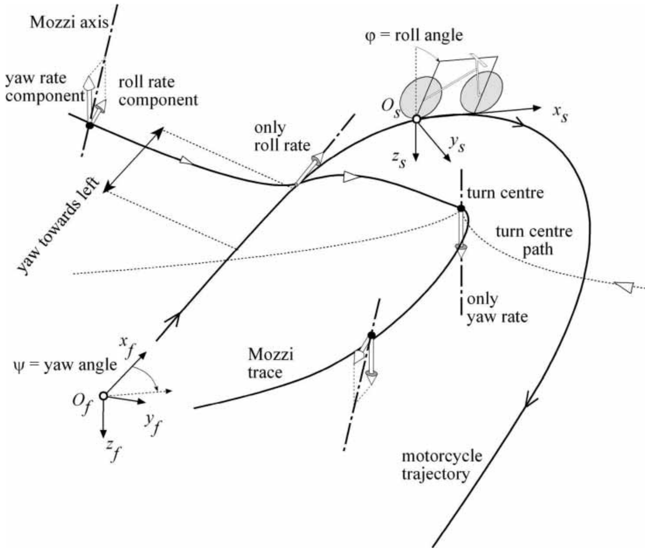

Figure 6. Theoretical motion of the Mozzi axis – a U-turn manoeuvre.

The assumption of negligible sideslip angle is acceptable, because most of the tyre lateral forces are generated by the presence of large camber angles [8].

The Mozzi trace is only displaced laterally with respect to the mobile coordinate system. The amplitude of ${}^s y_{\mathrm{M}}$ tends to infinity when the path of the motorcycle tends to be straight. The sign of ${}^s y_{\mathrm{M}}$ depends only on the sign of yaw rate: if $\dot{\psi} > 0$, the Mozzi trace lies on the right-hand side of the vehicle.

The Mozzi trace coordinates in the fixed coordinate system can be calculated by means of a matrix transformation, which depends on yaw angle ψ. In order to minimise the effects of measurement and computational errors, ψ was calculated by means of the coordinates of the motorcycle path measured with the high-frequency GPS.

In Figure 7, the loci of the Mozzi traces of the U-turn manoeuvres performed by the 125 cc motorcycle on dry and wet track are represented. When the motorcycle enters the curve, the Mozzi trace approaches the motorcycle from the left-hand side, because the yaw rate is negative during the counter-steer phase of the manoeuvre. The Mozzi trace crosses the path of the vehicle when the yaw rate is zero, then it passes on the right-hand side of the vehicle, because the motorcycle is now turning in the direction of the curve. The Mozzi trace during curve entering (A–D) shows large movements in the direction perpendicular to the motorcycle path, because there are fast variations in the components of angular velocity.

When the motorcycle moves in the central part of the curve (from D to G and from d to g, respectively), the Mozzi trace does not move so much, and its locus draws a cusp that points towards the centre of the curve. Actually in this phase of the manoeuvre, the yaw rate is dominant, and the point of the Mozzi trace closer to the path of the vehicle corresponds to the condition of minimum speed and maximum yaw rate (points E and F with dry track). After point G (g), the motorcycle begins the curve-exiting manoeuvre, and the Mozzi trace moves away from the path of the vehicle with some oscillations that correspond to variations in the components of angular velocity (Figure 5).

The centre of curvature of the path of the motorcycle can be calculated from the coordinates of the motorcycle path measured with high-frequency GPS. Figure 8 shows the loci described by the centre of curvature in dry and wet track conditions. Since a right curve is considered,

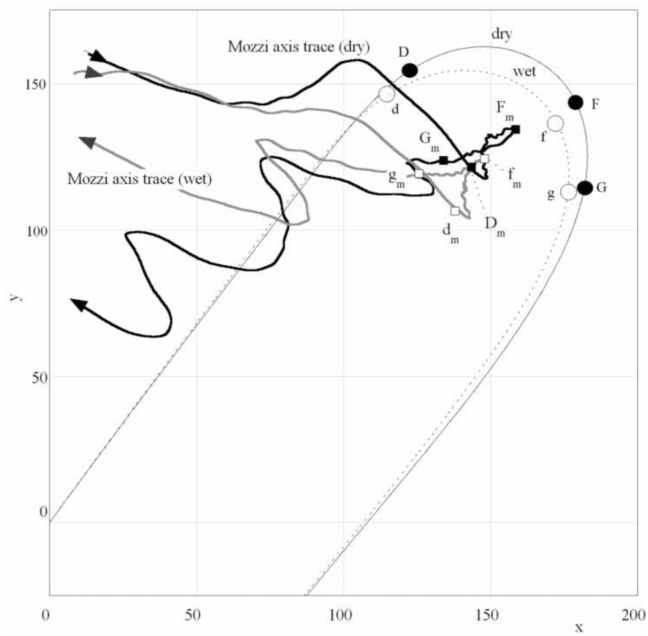

Figure 7. Loci of the Mozzi trace in U-turn manoeuvres (125 cc motorcycle).

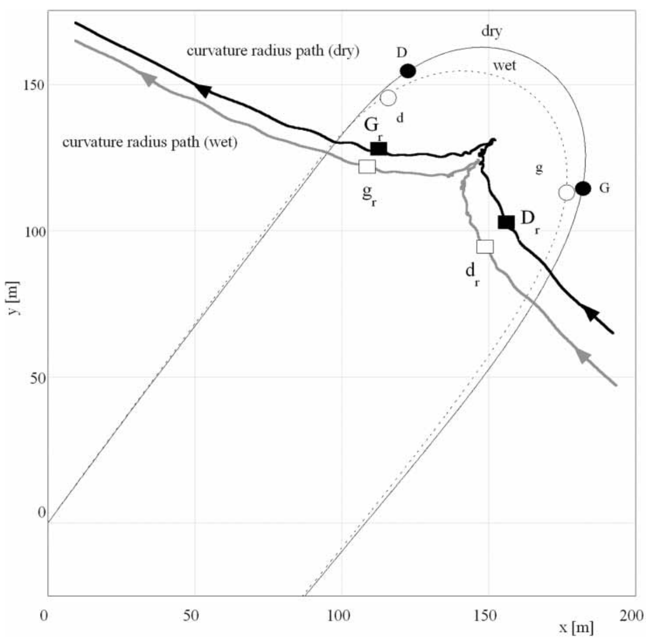

Figure 8. Loci of the centre of curvature trace in U-turn manoeuvres (125 cc motorcycle).

the centre of curvature approaches the trajectory of the motorcycle from the right-hand side moves towards the centre of the curve drawing a cusp and then moves away. Actually in the central part of the U-turn, which is nearly a steady turning manoeuvre, the loci of the Mozzi trace and of the centre of curvature are very close.

3.3. *Energy analysis of transient manoeuvres*

A quantitative criterion is needed to evaluate if a transient manoeuvre is exacting and close to a limit of lateral dynamics. The total kinetic energy of a motorcycle with the rider can be expressed as the energy associated with the motion of translation of the system as a single entity together with the energy related to the rotation of the system about its centre of mass:

$$E_k = E_{k_{\text{trans}}} + E_{k_{\text{rot}}}. \tag{3}$$

The kinetic energy related to translation is

$$E_{k_{\text{trans}}} = \frac{1}{2} m v_{\text{c}}^2. \tag{4}$$

where m is the mass of the vehicle and v_{c} the speed of the centre of the mass.

If the steer rotation and body motion are negligible, the kinetic energy related to the rotation of the system is

$$E_{k_{\text{rot}}} = \frac{1}{2}\{\omega\}^t[I_{\text{c}}]\{\omega\} + \frac{1}{2} I_{\text{f}} \omega_{\text{f}}^2 + \frac{1}{2} I_r \omega_r^2, \tag{5}$$

where $\{\omega\}$ is the angular velocity vector that depends on the roll, pitch and yaw velocities of the whole system and $[I_{\text{c}}]$ the inertia tensor of the whole system. If body axes are chosen, the inertia tensor is constant. I_{f} is the moment of inertia of the front wheel, I_{r} the moment of inertia of the rear wheel and ω_{f} and ω_{r} the rear and front wheel spin velocities. Actually, the first term is the rotational kinetic energy associated with the changes in orientation of the whole system, and it is named kinetic energy of orientation ($E_{k_{\text{or}}}$). The last terms are the spin kinetic energies of the wheels.

The time rate of the kinetic energy of orientation is

$$\frac{\mathrm{d}E_{k_{\text{or}}}}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{2}\{\omega\}^t[I_{\text{c}}]\{\omega\}\right). \tag{6}$$

The time rate is zero in a steady turning because the modulus of $\{\omega\}$ is constant and the vector direction does not change with respect to the body axes. The time rate of the kinetic energy of orientation is large in the presence of large variations in angular velocity; hence, it is well suited to highlight if a transient manoeuvre is exacting and close to a dynamic limit.

To show this characteristic, the U-turn manoeuvres on dry and wet track are considered. Figure 9 deals with the manoeuvres of Figure 5 and shows $E_{k_{\text{or}}}$ against time. Large variations in $E_{k_{\text{or}}}$ take place in the counter-steer phase (near point B), when the Mozzi trace moves

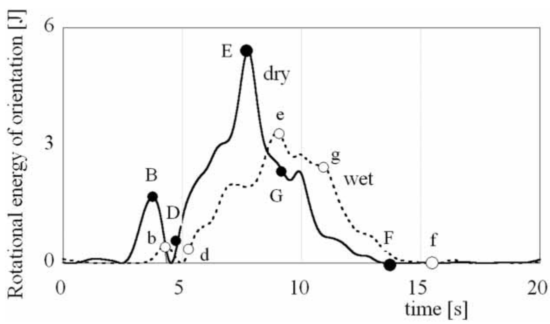

Figure 9. Kinetic energy of orientation in U-turn manoeuvres (125 cc motorcycle).

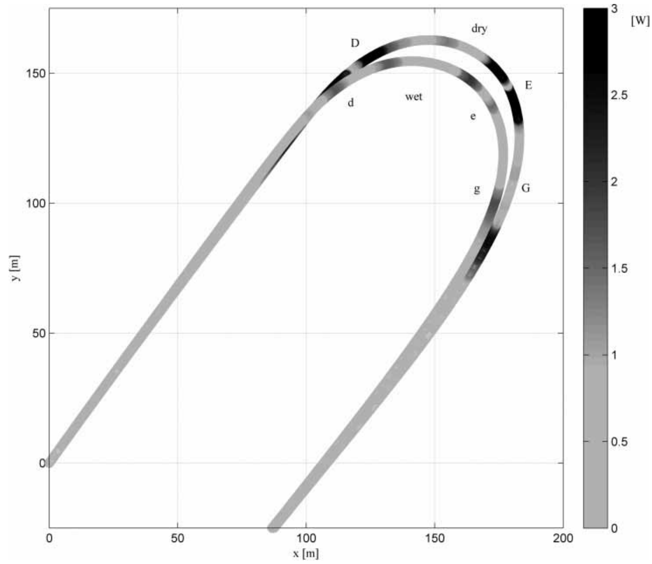

Figure 10. Time rate of kinetic energy of orientation in U-turn manoeuvres (125 cc motorcycle).

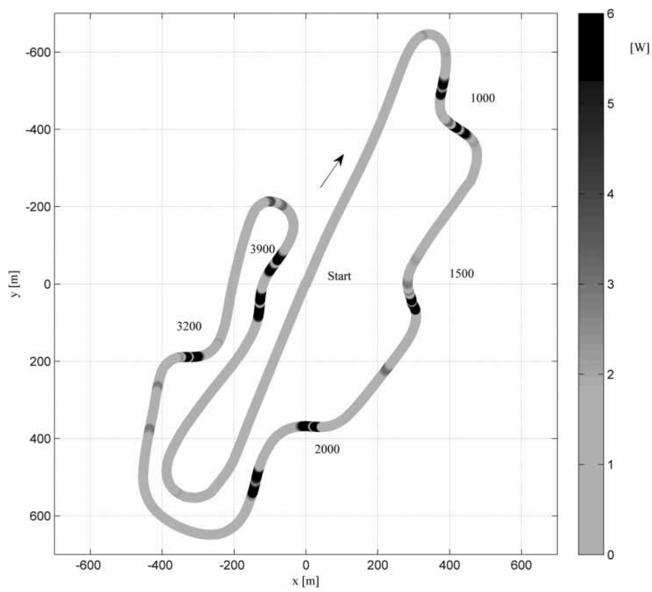

Figure 11. Time rate of kinetic energy of orientation in a race track (SBK motorcycle).

towards the curve centre (close to point D) and in the central part of the U-turn manoeuvre, near the peak of yaw rate (point E). When the ground is wet, the peaks are lower.

In Figure 10, the paths of the motorcycle are represented with levels of grey proportional to the modulus of the time rate of $E_{k_{\mathrm{or}}}$ (in Watt) calculated from measured data. When the track is dry, the darker spots occur close to point D and E and after point G. Typically, the darker zones are characterised by two dark spots at a small distance: the first spot corresponds to the increase in $E_{k_{\mathrm{or}}}$ and the second one to the decrease. Figure 5 and the Mozzi axis analysis show large variations in the components of angular velocity and large displacements of the Mozzi trace near point D and after point G. Near point E, large variations in the yaw velocity were measured.

When the track is wet, the dynamics limits are more stringent (reduced adherence), and there is a drastic decrement in time rate of $E_{k_{or}}$ (lower levels of grey), because the rider tends to smooth down the fast transient. Hence, the time rate of $E_{k_{or}}$ appears to be well related to the exacting phases of the manoeuvre and the dynamic limits.

The criterion based on the time rate of $E_{k_{or}}$ can be applied to the motion of a motorcycle along a whole circuit. Figure 11 deals with an SBK motorcycle running in the Mugello circuit, which is represented with levels of grey proportional to the modulus of the time rate of the kinetic energy of orientation. The darker the track, the more exacting the manoeuvre and closer to the limits of lateral dynamics. In the U-turns, small dark spots appear; they are similar to those of Figure 10. But the darkest spots occur when the motorcycle performs changes of direction at high speed (for example, the chicanes at 1000 m and 3900 m from the start) or very sharp changes of direction at lower speed (for example at 1500 m and 3200 m from the start).

4. Conclusions

The comparison between the manoeuvres carried out with dry and wet road highlights the different riding techniques and the difficult parts of the manoeuvres. The Mozzi axis analysis is useful for identifying the different phases of the manoeuvres (e.g. the counter-steer phase in curve entering) and for describing the geometry of the manoeuvres. Large movements of the Mozzi trace in the direction perpendicular to the motorcycle path occur when there are fast variations in the components of the angular velocity and are related to the most exacting phases of the manoeuvre.

The kinetic energy of orientation is a scalar index of the manoeuvre. Experimental data show that the largest values of the time rate of kinetic energy of orientation occur in the parts of the manoeuvre that are exacting for most riders (e.g. curve entering) and that the values of this quantity are related to road adherence, which is an important limit of motorcycle lateral dynamics.

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