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Experimental Analysis of Rider Motion in Weave Conditions

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ABSTRACT

Motorcycle dynamics is characterized by the presence of modes of vibration that may become unstable and lead to dangerous conditions. In particular weave mode shows large yaw and roll vibrations of the rear frame and out of phase oscillations of the front frame about the steering axis. The presence of the rider influences the modes of vibration, since the mass, stiffness and damping of limbs modify the dynamic properties of the system; moreover at low frequency the rider can control vibrations. Up to now very few experimental results dealing with rider's behavior in the presence of weave are available. This lack is due to the difficulty of carrying out measurements on the road and of reproducing the phenomena in laboratory. This paper deals with a research program aimed to measure the oscillations of rider's body on a running motorcycle in the presence of weave vibrations. First testing equipment is presented, it includes a special measurement device that is able to measure the relative motion between the rider and the motorcycle. Then the road tests carried out at increasing speed (from 160 to 210 km/h) are described and best fitting methods are used for identifying the main features of measured vibrations. The last section deals with the analysis of experimental results. The characteristics of the motion of the vehicle and of the rider (below and above the threshold of instability) are described in terms of amplitudes and relative phases. These results may be useful for validating numerical simulations.

Keywords: motorcycle, stability, weave, rider.

1 INTRODUCTION

The analysis of stability is a specific and important issue of the mechanics of two-wheeled vehicles. The first studies [1] highlighted the presence of a non-oscillatory capsizing mode and of two oscillatory modes (weave and wobble), which become unstable at certain speeds. Weave and wobble modes have a deep influence on safety and manoeuvrability of the vehicle.

In particular the weave mode, which is dealt with in this paper, has natural frequency that increase with speed and ranges from 2 to 4 Hz at high speed (> 60 km/h). This mode is unstable at low speed, well-damped in the medium speed range and not very damped at high speed. The modal shape of weave is characterised by large roll and yaw vibrations of the rear frame of the motorcycle and by oscillations of the front frame about the steering axis out of phase with yaw [2].

After the first pioneering studies, research in the field of motorcycle stability on the one hand aimed to improve the motorcycle model (including the effect of frame flexibility [3] or modelling tires with more details [4]) and on the other hand aimed to add a rider model to the motorcycle model. The latter topic of research is supported by practical riding experience that suggests a large effect of rider on the control of instabilities. In recent years many papers dealing with realistic models of rider's control have been developed, see for example [5].

The passive response of rider's body in the presence of vibrations of the motorcycle is of great interest as well, since rider's impedance may contribute to suppress unstable vibrations. Research in this field requires the measurement of the response of rider's body, the identification of body parameters, the development of body models and their implementation in the multibody codes for the study of stability. Recently, rider's passive steering impedance has been identified by means of laboratory tests and its effect on motorcycle stability has been analysed by means of a multi-body code [6].

This paper deals with the measurement of rider's response to weave oscillations of an actual motorcycle on the road. It is organized as follows: the experimental equipment and methods are presented in section 2, fitting methods for the identification of the main features of motorcycle and rider's vibrations are presented in section 3, results are shown and discussed in section 4.

2 TESTING EQUIPMENT AND METHODS

The choice of the motorcycle for road tests was made with special attention to the possibility of highlighting weave phenomena, placing measurement equipment and improving rider safety. The selected motorcycle is a prototype touring motorcycle (300 kg in riding conditions with displacement larger than 1000 cm^3 and wheelbase larger than 1.6 m. The prototype was equipped with a particular set of tires in order to reach weave conditions without difficulty.

To perform the tests an experienced professional rider 1.7 m high (82 kg in riding conditions) was chosen. Since the tests focus on movements of the rider in weave condition, the rider was instructed to behave normally in weave condition, without removing the hands from the handlebar.

The vehicle was equipped with several sensors including: an angular potentiometer for the measurement of steering angle, a compact inertial measurement unit with three accelerometers and three gyrometers and a GPS unit for speed and trajectory acquisition. The inertial measurement system was placed on the rear frame of the motorcycle, on the top of the fuel tank cover close to the steering plate.

For describing rider movements during oscillatory events, two degrees of freedom were considered according to the scheme of Figure 1. The first degree of freedom is lateral displacement of the lower body of the rider y_r with respect to the motorcycle and it is modelled by means of a prismatic joint between the lower body and the motorcycle. The second degree of freedom is upper body tilt θ_r with respect to the motorcycle and it is modelled by means of a revolute joint.

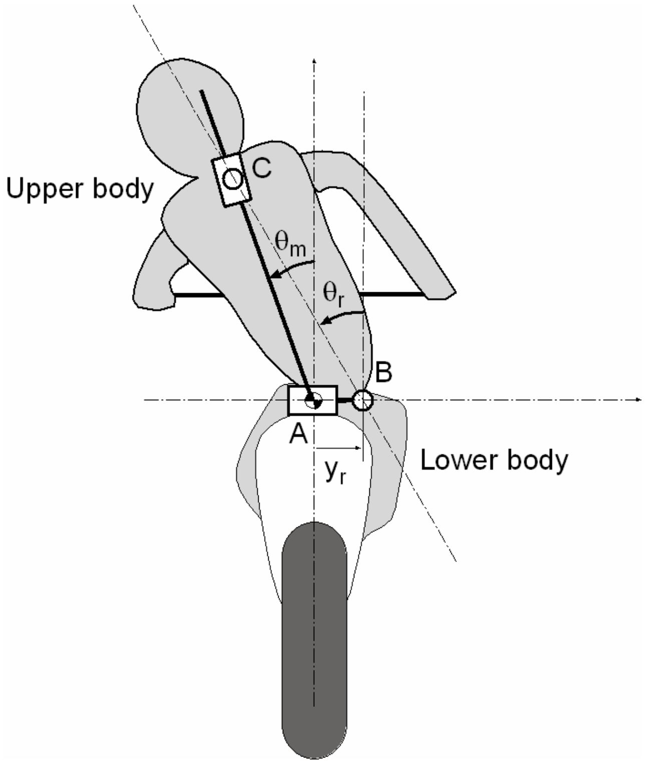

Figure 1 Measurement scheme.

The rider lateral displacement was measured by means of a linear potentiometer connected to the rider and to the motorcycle. The upper body tilt was measured by means of an oscillating lever connected to rider shoulders and the motorcycle and equipped with an angular potentiometer. Actually, rotation θ_m of the oscillating lever does not represent rider's tilt, but there is a geometric relation between the two angles, which can be obtained solving the loop equation of triangle ABC of figure 1:

$$\theta_r = \theta_m + \arcsin\left(\frac{y_r \sin(\theta_m + \pi/2)}{L_{BC}}\right) \tag{1}$$

In Equation (1) L_{BC} is the fixed length between rider' pelvis and shoulders. Since y_r is much smaller than L_{BC} , θ_r is very close to θ_m.

In addition to these sensors a small camera was placed on the back of the motorcycle to capture videos of the rider's movement with respect to the motorcycle and an extra camera was placed on a car that followed the motorcycle during tests to record absolute movements of motorcycle and rider during weave oscillations.

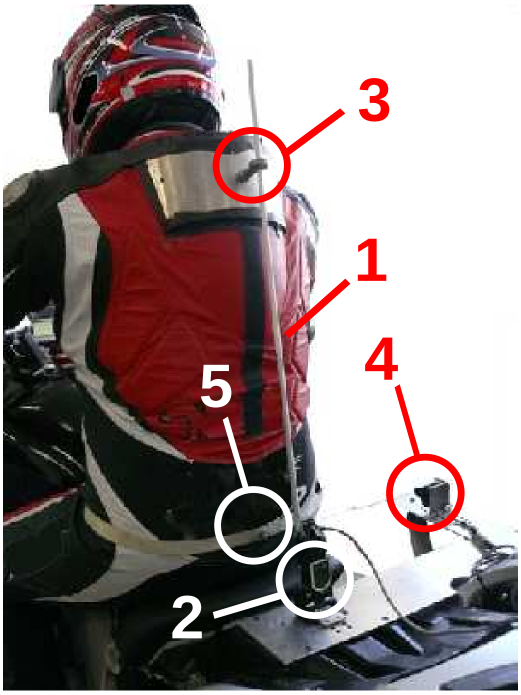

Figure 2: Measurement equipment: 1-oscillating lever, 2-revolute joint and angular potentiometer 3-ball in cylinder connection to rider shoulders, 4-linear potentiometer, 5-ball-joint connection to lower body of the rider.

Weave tests were carried out at four different speeds: 160, 180 (high speed), 200 and 210 km/h (very high speed). At high speed the weave vibration had to be initiated by an external disturbance and the tests were carried out in the following way: when the desired speed was reached, the rider locked the throttle with a special device, afterwards the rider excited the motorcycle by means of an impulse torque on the handle bar and let the bike free to oscillate e until a complete extinction of oscillations was reached. At very high speed weave vibration was self-sustained, the rider reached the desired test speed, locked the throttle and let the bike free to oscillate for a few of seconds. Afterwards the rider slowed down the velocity to let the oscillation die out quickly. The tests were carried out on a straight road and were repeated at least five times for each speed.

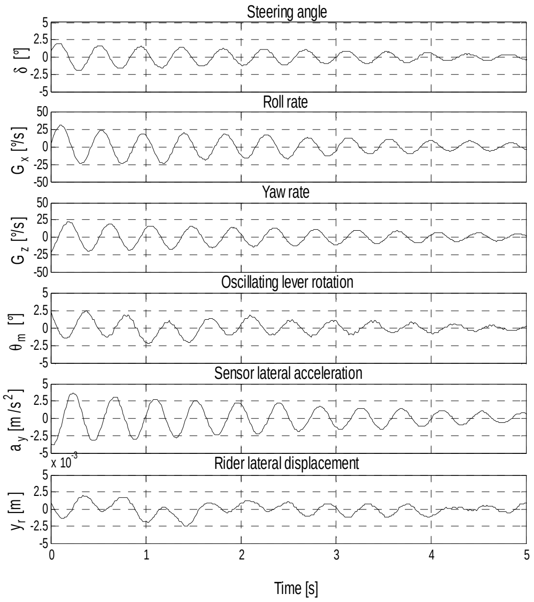

Figure 3. Measured motion parameters at 160km/h.

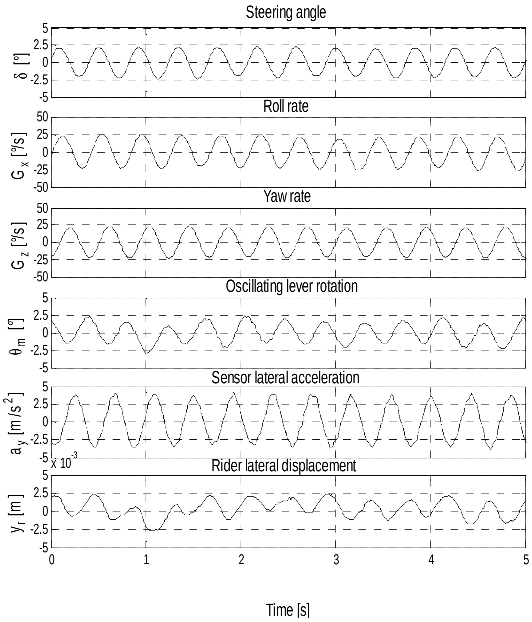

Figure 4. Measured motion parameters at 210km/h.

Figure 3 shows an example of kinematic parameters of the motorcycle (steer angle δ, roll rate G_x, yaw rate G_z, lateral acceleration a_y) and of the rider (rider lateral displacement y_r and oscillating lever rotation θ_m) measured during a high speed test

The oscillations vanish rather quickly, since at 160 km/h weave is still stable. The plots of motorcycle parameters highlight the presence of only one period of oscillation and hence there is a dominant mode. The plots of oscillating lever rotation and – especially – of rider lateral displacement show the presence of a very low frequency oscillation superimposed to the dominant mode. The maximum amplitude of rider lateral displacement (2.5 mm) is very small if compared with shoulders displacement caused by rider tilt (about 20 mm).

Figure 4 shows the kinematic parameters of motorcycle and rider measured when weave is self-sustained.

3 FITTING METHODS

When weave is excited by the rider the vibration is damped, and a good mathematical law for fitting measured data is the equation of damped harmonic vibrations:

$$S\left(t\right) = S_0 e^{-\omega_n \zeta t} \cdot \sin\left[\left(\sqrt{1-\zeta^2} \cdot \omega_n\right) t - \phi\right] = S_0 e^{-\omega_n \zeta t} \cdot \sin\left[qt - \phi\right] \quad (2)$$

In which:

- $S(t)$ = time evolution of the signal
- S_0 = amplitude
- $\omega_n = 2\pi f_n$, undamped natural pulsation, in which f_n is undamped natural frequency
- ζ = damping ratio
- $q = 2\pi f$, damped pulsation in which f is the damped natural frequency
- ϕ = phase.

The steering angle was considered as the input of the mechanical system composed by the motorcycle and the rider. For this reason it was the first signal fitted with the model of equation (2). The obtained frequency (f_n) was chosen as the frequency of all other signals, whereas S_0, ζ and ϕ were determined separately, for each signal, by means of equation (2).
When weave is self-sustained, equation (2) is used again for fitting, some preliminary tests showed that the accuracy of fitting improved when ζ was set to zero.

Examples of fitting are represented in Figure 5 and 6, the fitting curves match accurately measured data: steering angle, roll rate, yaw rate, oscillating lever tilt, lateral acceleration, and lower rider lateral displacement.

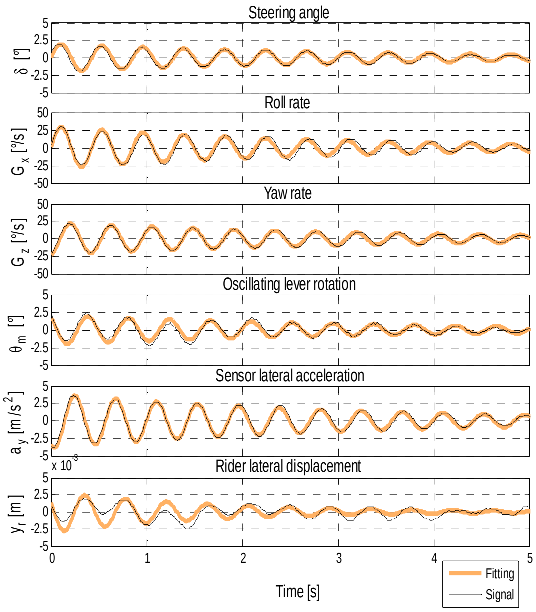

Figure 5. Measured motion parameters vs fitting at 160km/h.

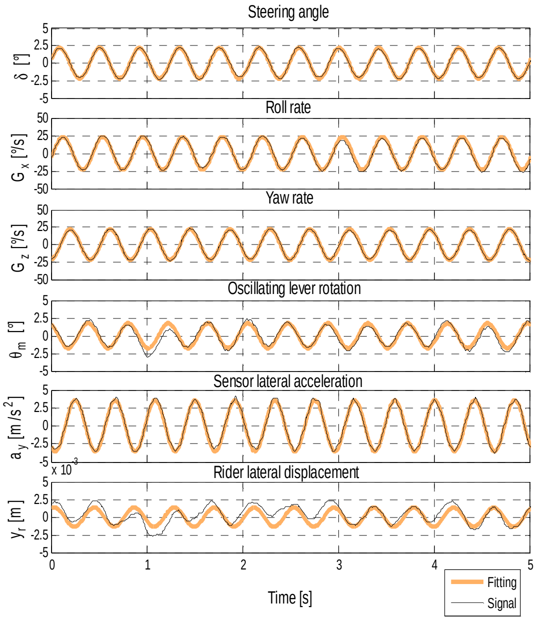

Figure 6. Measured motion parameters vs fitting at 210km/h.

As mentioned in chapter 2 the difference between θ_r and θ_m is small, Figure 7 shows examples of rotation of the oscillating lever θ_m and rider's tilt θ_r. Since the difference is negligible with respect to θ_r (lower than 10%) all elaborations and analysis were carried out with the assumption $\theta_r = \theta_m$.

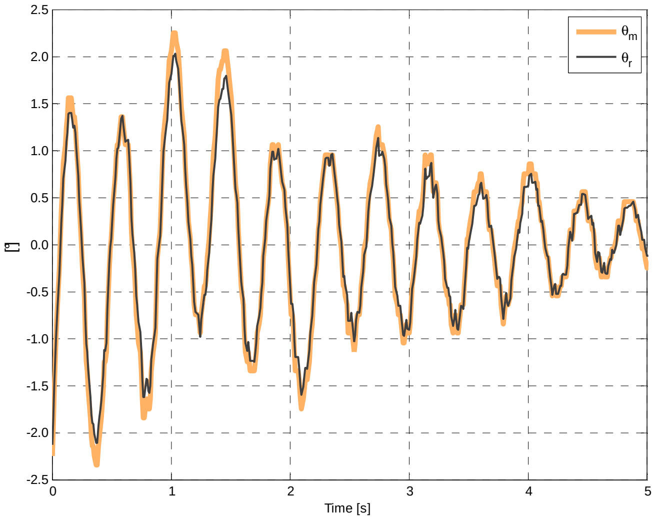

Figure 7. Comparison between oscillating lever angle θ_m and rider's tilt θ_r.

In order to have a more exhaustive representation of weave and wobble modal shapes, the fitted angular speeds (G_x and G_z) and linear acceleration (a_y) were further processed in order to obtain the corresponding angular and linear displacements. The assumption of small oscillations was made and equation (2) was directly integrated. The following equations hold:

$$\varphi(t)=\int G_x(t)\,dt=\frac{(G_x)_0}{\omega_n}e^{-\omega_n\zeta t}\cdot\sin\left[\left(\sqrt{1-\zeta^2}\cdot\omega_n\right)t-\left(\arcsin(\zeta)+\frac{\pi}{2}+\phi\right)\right] \quad (3)$$

$$\psi(t)=\int G_z(t)\,dt=\frac{(G_z)_0}{\omega_n}e^{-\omega_n\zeta t}\cdot\sin\left[\left(\sqrt{1-\zeta^2}\cdot\omega_n\right)t-\left(\arcsin(\zeta)+\frac{\pi}{2}+\phi\right)\right] \quad (4)$$

$$Y(t)=\iint a_y(t)\,dt=\frac{(a_y)_0}{\omega_n^2}e^{-\omega_n\zeta t}\cdot\sin\left[\left(\sqrt{1-\zeta^2}\cdot\omega_n\right)t-\left(2\arcsin(\zeta)+\pi+\phi\right)\right] \quad (5)$$

4 ANALYSIS OF RESULTS

The fitting methods of section 3 made it possible the identification of the modal characteristics of weave. The natural frequencies and the damping ratios identified in the various tests at different speeds are represented in figures 8 and 9. Figure 8 shows that the values of natural frequency obtained in the various tests at the same speed are very similar (the range is only 0.25 Hz) and that weave frequency increases slightly with speed. The values of damping ratio are less repeatable than the ones of natural frequency, but figure 9 clearly shows the transition between stable weave and self-sustained weave, since the damping ratio tends to zero above 190 km/h. Average values of natural frequency and damping ratio are summarized in table 1. The measured values and trends are in agreement with the ones presented by other authors [7], if the different weights and geometric characteristics of the motorcycles are taken into account.

Table 1. Average values of natural frequency and damping ratio.

Speed [km/h]	160	180	200	210
Frequency [Hz]	2.33	2.34	2.44	2.40
Damping %	2.40	1.87	-	-

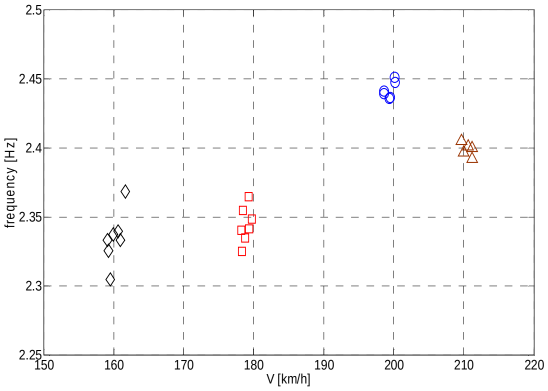

Figure 8. Identified weave frequency against speed.

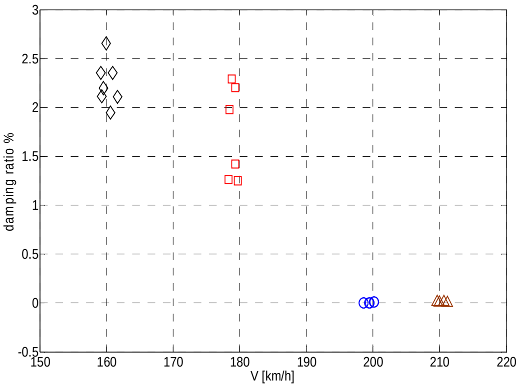

Figure 9. Identified weave damping ratio against speed.

The measured weave is a combination of several components of motion: steer oscillation δ, roll φ, yaw ψ, lateral displacement y, rider tilt θ_r and rider displacement y_r (negligible), which define the modal shape. The modal shape of weave at the different speeds is represented by compass plots in which the length of the arrow is proportional to amplitude of each component and the angle represents the phase lag of each component with respect to steer. In order to obtain homogeneous components, lateral displacement y is normalized with respect to wheelbase. Then, since only the ratios between components are relevant, the amplitudes of modal components are normalized with respect to the largest.

It is possible to draw a compass plot for each test at assigned speed. A preliminary analysis showed that the modal shapes identified from the various tests carried out at the same speed are very repeatable. Therefore the average modal shapes are calculated for each speed. Figures 10 shows the compass plots of the average modal components in the stable range (high speed tests).

The largest component is rider tilt and it lags behind steer rotation of about 230°. The roll component of motorcycle vibrations is large and lags behind steer of about 100°. The yaw component is a bit smaller than roll and the phase lag is about 180°. Normalized lateral displacement is the smallest component and shows a phase lag of 300°. There is no significant difference between the compass plots at 160 and 180 Km/h.

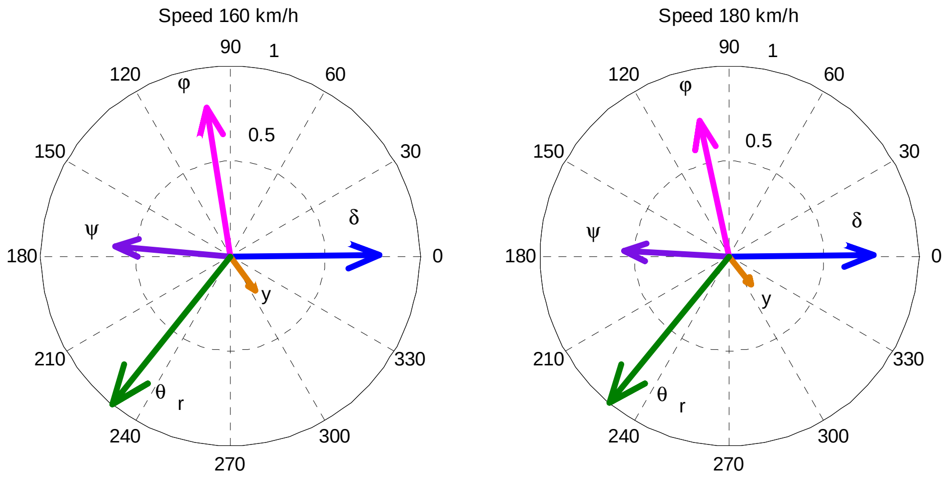

Figure 10 Modal shapes of stable weave.

Figures 11 show the compass plots of the average modal shapes in the range of self-sustained weave. In this range of speeds the largest modal component is steer rotation, rider tilt is still larger than roll and yaw. The phase lags of roll, yaw, rider tilt and lateral displacement increase of about 10°. The phase difference between rider tilt and motorcycle roll is about 130°.

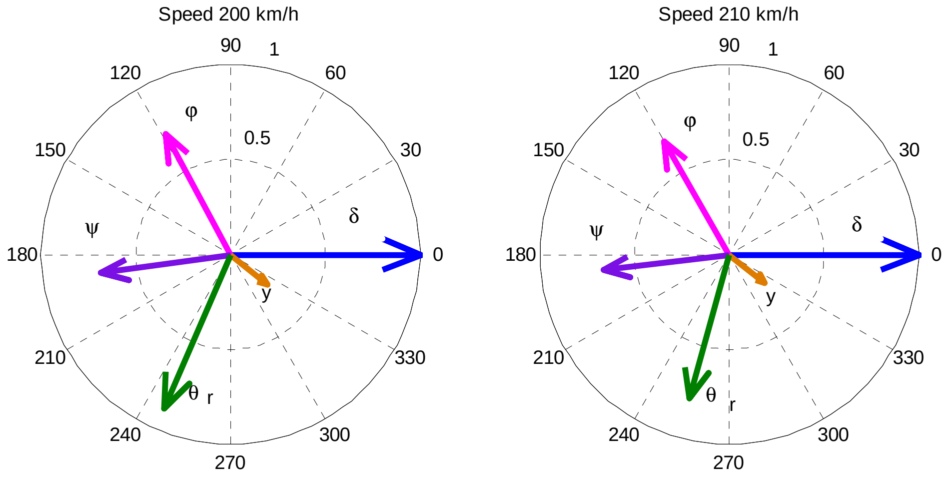

Figure 11 Modal shapes of self sustained weave.

Both the amplitudes and the phases of motorcycle's modal components are in agreement with experimental values [8] and numerical values [3] relative to other motorcycles. A comparison between rider tilt measured in the framework of this research and the one measured by means of laboratory tests [9] [10] is possible, even if in laboratory tests the input was a roll motion of the motorcycle frame. In the present research at 160 km/h weave frequency is 2.33 Hz, the ratio between rider tilt amplitude and roll amplitude is 1.25 and rider tilt lags behind roll of about 130°. Typical values at the same frequency reported in [9] are 3 and 170° respectively. In [10] it is shown that at 2.5 Hz tangential acceleration due to rider tilt has a phase lag of about 180° with respect to tangential acceleration caused by roll motion. Hence, the agreement between phases is quite good and it confirms that upper body relative tilt tends to oppose to motorcycle roll.

5 CONCLUSIONS

The analysis of experimental results collected during road tests gives some hints useful for the development of models of passive response of rider's body. When weave is excited, upper body relative tilt is an important component of motion, whose amplitude is larger than or comparable with motorcycle's roll. Lateral displacement of the lower body with respect to the saddle is very small and difficult to measure owing to the presence of clothes. The time history of upper body relative tilt essentially shows only one dominant harmonic component, hence a one degree of freedom model may be enough to represent the most important features of rider's passive response. Upper body relative tilt lags behind vehicle roll of about 130°, hence it opposes to motorcycle roll. This result suggests that the rider tends to maintain the upright position in the presence of weave vibrations and agrees with sensations of riders and video recordings. The transition from stable weave to self-sustained weave leads to minor modifications in the modal shape: an increase in phase lags and a decrease in the amplitude of rider's relative tilt.

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