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Experimental Research on Motorcycle Stability and Rider Control during Cornering Braking

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ABSTRACT

The aim of this research is to understand the stability behaviour of the motorcycle while braking in corners and how the rider controls the motorcycle during this state. The stability performance of the motorcycle in straight line and during steady state cornering is initially studied through multi body dynamic simulations. Experimental evaluations are then carried out to estimate the difference in stability performance between straight line and corners. The results of this study show that there is a frequency shift and damping change in weave mode during cornering when compared to straight line. With this understanding, a numerical and experimental study is performed to understand the vibration modes occurring while decelerating a motorcycle in a corner. The frequency and amplitude of the excited vibrational modes in this condition are estimated. The control of the motorcycle in this condition by the rider is then studied by measuring the steering and body inputs given by the rider. The results of this study are then compared with straight line braking. A contribution analysis is then performed to identify the most contributing rider control input for maintaining stability. The results of this study show that steering input by the rider is the major contributing factor for maintaining stability. A correlation study is then performed to understand the relationship between the steering torque applied by the rider and the lateral oscillations generated on the vehicle. It is found that the steering torque applied by the rider correlates well with both roll and yaw oscillations. A regression analysis is then performed to estimate the relationship between steering torque and lateral excitations of the vehicle. It is shown that this relationship can be used to develop a steering control algorithm which assists riders during braking in corners.

Keywords: Motorcycle Dynamics, Stability, Corner Braking, Rider Control.

1 INTRODUCTION

The growth of motorcycles in India has been phenomenal, primarily due to their low cost and high fuel efficiency. The average speed of motorcycles has been increasing over the years and there is an increased demand for safety. Extensive research is being carried out in the area of motorcycle dynamics to improve safety. Studies on road accidents show that ineffective braking during cornering is one of the major causes for two wheeler accidents in India [1]. This is because the road infrastructure and traffic conditions in developing countries require the rider to decelerate the vehicle frequently, even while turning and cornering. Improvement in stability and control of the motorcycle during these conditions is very significant considering the enhancement in safety it could deliver.

The inherent design of any two wheeled vehicle generates instabilities while riding. Studies on motorcycle stability are generally based on modal analysis and they show that weave, wobble, capsize and chatter are the dominant vibration modes [2-5]. These studies majorly focus on stability in straight line when the lean and yaw angles of the motorcycle is zero. During cornering or while negotiating a turn, when the lean and yaw angles of the motorcycle is non-zero, coupling of in plane and out of plane vibrational modes occur due to the changes in motorcycle geometry and generation of tyre lateral forces and moments [6]. This causes interactions between vertical, longitudinal and lateral motions of the motorcycle and hence changes the stability behavior of a motorcycle. When transient conditions like acceleration and braking are introduced during cornering, motorcycle stability behavior is further modified [7].

During braking the rider maintains stability through steering and body inputs. If the stability of the motorcycle is high, the rider inputs required to stabilize the motorcycle during braking is minimal. However when the operating speeds are high and also when braking happens in a corner, the inputs required to stabilize the motorcycle will be higher. This is primarily due to the reduced reaction time available for braking and the reduction in the stability of the motorcycle during such scenarios [8]. It is possible to overcome these difficulties if assistance is provided to the rider to maintain stability of the motorcycle during braking. To provide such assistance, it is important to understand the stability behavior of the motorcycle during braking. It is also significant to understand the control of the motorcycle by the rider during braking.

In this work, the stability of the motorcycle in straight line and corners is studied using numerical and experimental methods. Then an experimental approach is used to understand the impact of straight line and cornering braking on the stability of the motorcycle. With this understanding, the rider control inputs used to maintain the stability of the motorcycle during straight line and cornering braking is estimated. The dominant rider control input to maintain stability during braking is determined. The correlation between rider control input and lateral oscillations of the vehicle during braking is studied. A frequency domain analysis is then performed on the inputs given by rider during braking. Based on these results, the relationship between the inputs given by the rider to maintain stability during braking and the lateral oscillations of the vehicle is estimated using regression analysis.

2 MOTORCYCLE STABILITY IN STRAIGHT LINE AND CORNERS

Stability of a motorcycle is defined as its ability to retain its state of dynamic equilibrium under all riding conditions. Stability is generally characterized by in plane and out of plane vibrational modes. The natural frequencies, mode shapes and damping characteristics of these modes are estimated using Eigen value analysis and are analyzed to estimate the stability performance of a motorcycle. Among the out of plane stability modes of a motorcycle, weave is a low frequency, high energy mode associated with the rear yaw, lateral motion and roll of the motorcycle [9]. Weave mode is excited at high speeds due to the lateral forces that are induced to the motorcycle. During cornering, transient conditions like braking cause fluctuations to the lateral forces and these fluctuations can excite weave. To understand this phenomenon, weave stability of the motorcycle in straight line and cornering is studied using Multi Body Dynamic (MBD) simulation.

A MBD model of the motorcycle is modelled using commercially available software VI-Motorcycle, as shown in Figure 1. The specification of the motorcycle used for the analysis is given in Annexure 1. There are nine subsystem assemblies in the model: front fork, rear suspensions, front wheel, rear wheel, engine, driveline, brakes, frame and rider. The model has eleven degrees of freedom which includes four rotations (steering pivot, the swing arm pivot and both the wheels), one translation (front telescopic fork) and six degrees of freedom for the frame assembly. The subsystems of the motorcycle are chosen as rigid bodies including rider. The detailed construction of the MBD model for a motorcycle can be referred from the research paper by Karanam et al [10]. The tire model by Pacejka is used in this MBD model [11]. The details of the spring-damper properties of the suspension system, mass-inertia of the motorcycle subsystems and tire properties are given Annexure 2. An Eigen value analysis is performed using this model to understand weave stability in straight line and during corners. The results of the same are given in Figure 2 .

The results show that the negative real part of weave mode is higher during cornering when compared to straight line. It can also be seen that, with the increase in cornering radius the negative real part is reduced. This shows that weave damping is increased during cornering when compared to straight line. Also, when lateral accelerations are increased, weave damping is slightly increased at lower velocities but remains the same at higher velocities. Natural Frequency of the weave mode increases with velocity but there is no change in the natural frequency of the weave mode between straight line and cornering. Further to understand, the same motorcycle is experimentally evaluated for weave stability in straight line and while cornering. Weave stability test is performed in straight line at different velocities. In this test, the motorcycle is driven straight at constant velocity and a steering shake is given by the rider. The yaw rate is measured using an inertial measuring unit and the frequency spectrum of yaw rate is estimated. From the frequency spectrum of yaw rate, the natural frequency and damping ratio for weave mode are estimated. Frequency spectrum of yaw rate at 33m/s is given Figure 3 and the measured weave damping ratios are given in Figure 4. Weave stability in a corner is then experimentally estimated by riding the motorcycle in a corner of radius 70m at different velocities. Yaw rate is measured during the test and the frequency spectrum of yaw rate is estimated. The frequency spectrum of yaw rate is shown in Figure 5.

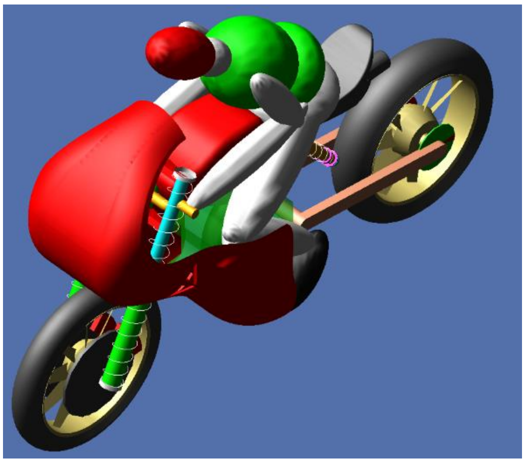

Figure 1: MBD Model of the motorcycle

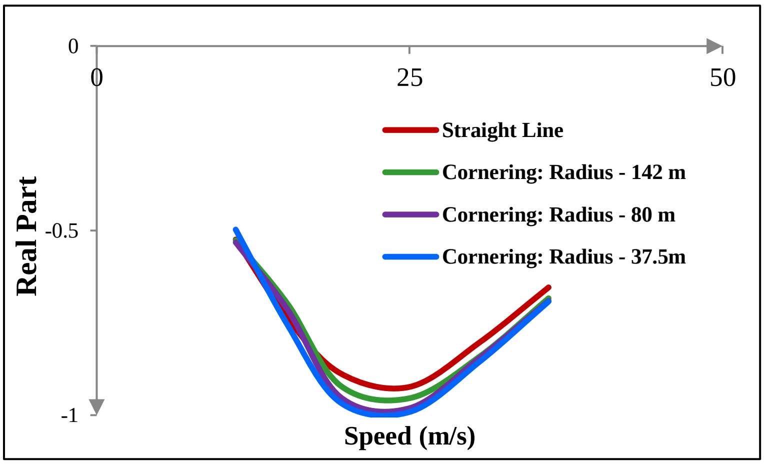

Figure 2: Weave Stability – Real Part

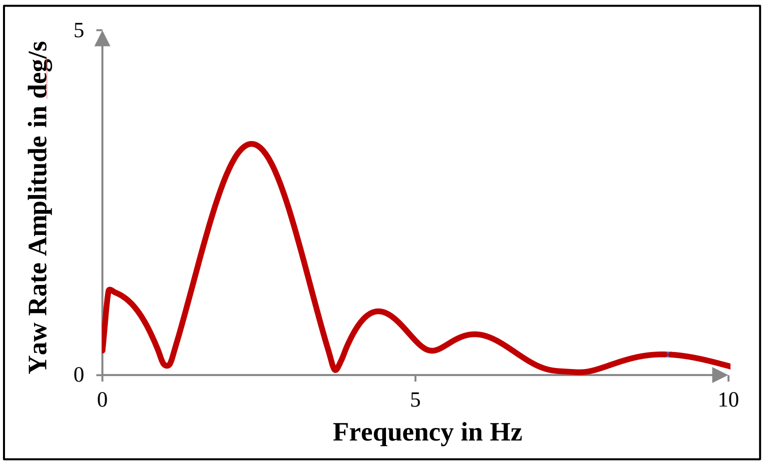

Figure 3: Yaw rate Frequency Spectrum at 33m/s

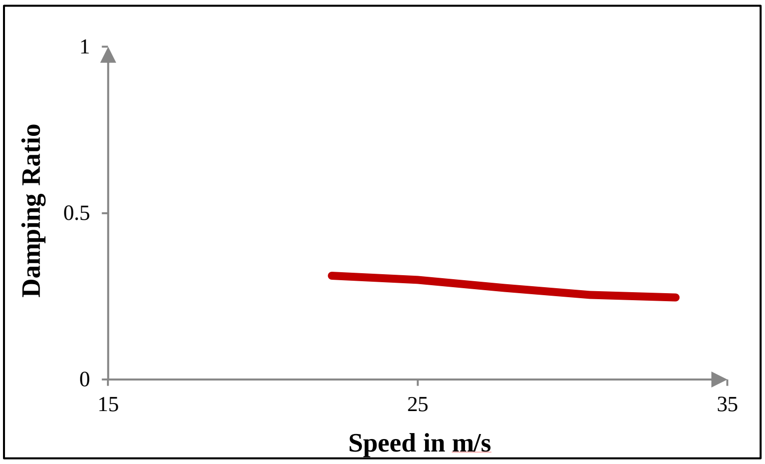

Figure 4: Weave Damping Ratio in Straight line

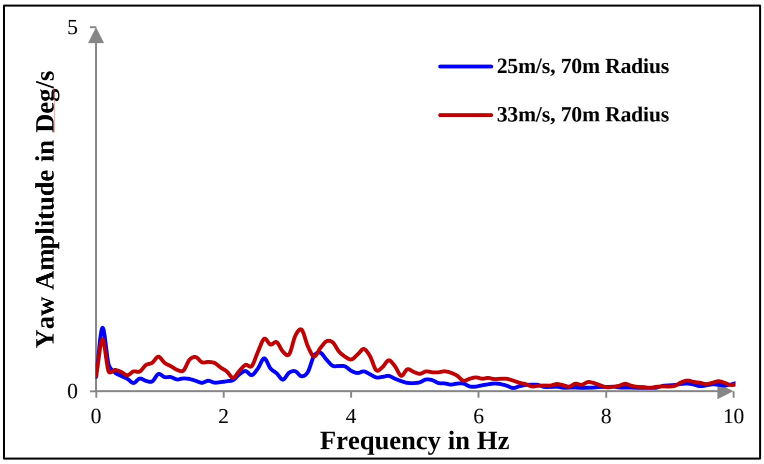

Figure 5: Yaw rate Frequency spectrum during cornering

The results of the experimental evaluation for weave stability in straight line and cornering show that the damped natural frequency of weave mode for the test motorcycle is around 2-3 Hz in both straight line and cornering. The damping of the weave mode is increased during cornering when compared to straight line. This can be seen in the frequency spectrum where amplitude of yaw rate is significantly reduced and the resonance peak occurs in a wider frequency band when compared to straight line. When velocity is increased, the damping of weave mode is slightly reduced and the amplitude of weave mode is increased. These findings give a basic understanding on the weave stability during cornering. Rider control during cornering depends on the ability of the motorcycle to dampen these instabilities.

3 VIBRATION MODES DURING BRAKING IN A CORNER

The instabilities during cornering are further amplified when transient forces like braking are introduced. The forces and moments generated during front braking in a corner will cause the motorcycle to lift up and yaw out of the corner where as the same during rear braking will cause the motorcycle to roll and yaw into the corner [12]. The friction limits and the lateral stiffness of the tires will be reduced due to the longitudinal forces that are generated during braking while cornering [13, 14]. This will further reduce the stability of the motorcycle. The control of these instabilities by the rider will depend on the frequency and amplitudes at which they occur. To understand this control, the stability of the motorcycle while braking in a corner is studied using an experimental approach. The test motorcycle is instrumented with a data logger, GPS and an inertial measuring unit. The test motorcycle is driven in a corner at constant velocity and maximum braking is applied to stop the vehicle. This procedure is repeated at multiple velocities for both front and rear brakes. Yaw and Roll rates of the vehicle are measured for each trial. Frequency spectrum of yaw and roll rates during braking is estimated to study the vibrational modes that are excited when front and rear braking is applied during cornering. The results of this study at 0.35g lateral acceleration are shown in Figures 6 and 7.

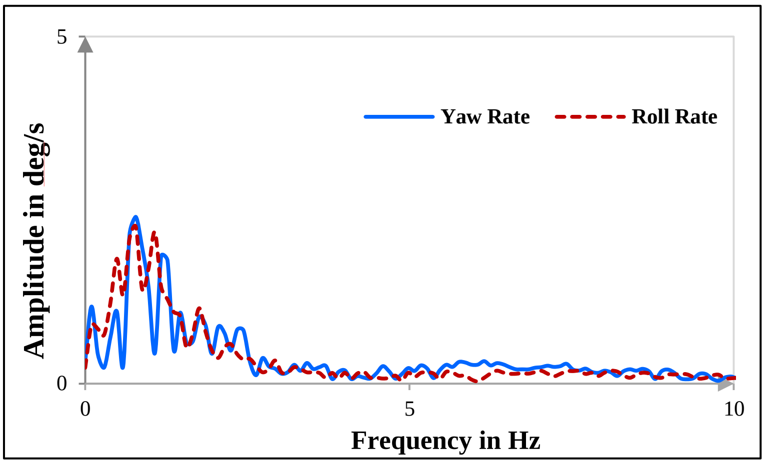

Figure 6: Yaw and Roll rate Frequency spectrum for Front Braking at 0.35g Lateral Acceleration

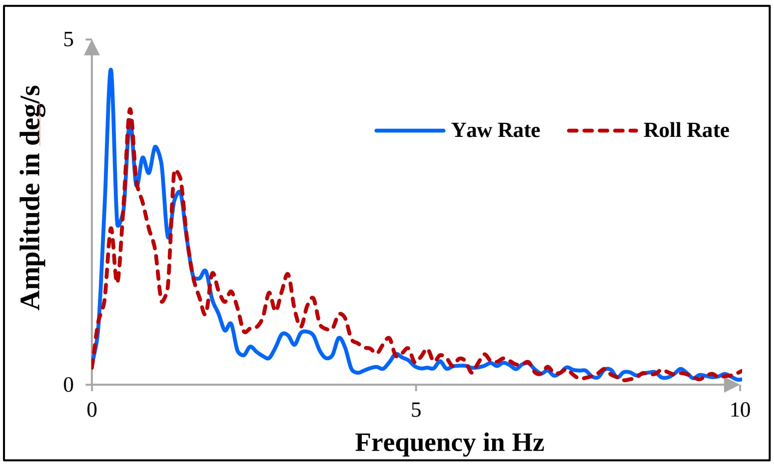

Figure 7: Yaw and Roll rate Frequency spectrum for Rear Braking at 0.35g Lateral Acceleration

The results show that the yaw and roll disturbances during front and rear braking in a corner occur below 5Hz. The amplitude of yaw disturbances is higher in rear braking when compared to front braking. The peaks are dominant between 0 to 2 Hz and multiple frequency peaks are observed in this zone. The average amplitude of yaw disturbances is close to 2 deg/s for front braking and 7 deg per second for rear braking in this test condition. The amplitude for roll disturbances is also higher in rear braking when compared to front braking. The peaks are dominant between 0 to 1 Hz and the average amplitude is around 2deg per second for both front and rear braking. Similar findings are observed for higher lateral accelerations as well. When lateral accelerations are increased, the frequencies of both roll and yaw disturbances are below 5Hz, however the amplitudes of the disturbances are increased. It can also been seen that the peaks of roll and yaw frequencies are close to weave natural frequency. Therefore improvement in weave stability of the motorcycle can help to minimize the disturbances during braking in a corner.

4 RIDER CONTROL DURING CORNERING BRAKNG

Next step is to understand the control of the motorcycle by the rider when these disturbances occur. An experimental approach is developed to study this phenomenon. In this approach, the dominant control input given by the rider is initially estimated. The correlation of this control input with respect to the lateral disturbances of the vehicle is then studied. The frequency at which the control input is given by the rider is estimated. With this understanding, the relationship between the control input and the lateral disturbances are estimated through linear regression analysis.

4.1 Estimation of the dominant Rider Control Input

The rider controls the motorcycle through steering and body inputs [15]. These inputs are given based on his perception of the roll and yaw disturbances that occur. An experimental study is performed to understand how rider controls the motorcycle during braking in straight line and while cornering. In this study steering torque and body input forces are measured during these conditions and a correlation analysis is performed to understand the contribution of the inputs given by the rider [16]. Steering torque is measured using a piezoelectric torque sensor and body inputs are measured at the tank using load washers. The test motorcycle is also instrumented with an inertial measuring unit to measure the lateral disturbances that occur during braking. A correlation analysis is then performed between the inputs and the deceleration measured for both straight line and cornering braking. The results of this analysis are given in Figures 8 and 9. The results show that during straight line braking, body inputs show a good correlation with deceleration. During cornering braking, steering input show a better correlation when compared to body inputs. These results show that while braking in a corner, the most contributing control input given by the rider is steering torque and during straight line braking it is body inputs. These results are similar for both front and rear braking. This evaluation has been performed with multiple riders and similar results are observed.

4.2 Correlation between Rider Control Input and Lateral Disturbances

The relationship between steering torque input given by the rider and the lateral disturbances of the vehicle is experimentally studied for braking in straight line and cornering. The instrumented test motorcycle is evaluated for straight line braking and cornering braking at multiple velocities and lateral accelerations. Steering torque, yaw/roll angles and rates are measured during the test. A correlation analysis is then performed to identify the relationship between steering torque applied by the rider to control the motorcycle and the lateral disturbances. The results of the correlation analysis are given in Figures 10, 11, 12 and 13

The results show that, steering control is completely different for front and rear braking in a corner. Roll angle and roll rates are negatively correlated during front braking in corner whereas roll angle is positively correlated and roll rate is negatively correlated for rear braking. This is because, during front braking in a corner, the roll angle of the motorcycle reduces due to the moment created by the front longitudinal force. The rider control required during this scenario will be an increase in steering torque such that roll angle further reduces. However during rear braking in a corner, the roll angle of the motorcycle tends to increase due to the moment created by the rear longitudinal force, thereby increasing the roll rate. Rider control in this scenario will be an increase in steering torque to reduce roll angle. Initially due to the braking forces, the roll rate will be in the opposite direction but once steering torque is applied, roll rate tends to change its direction. Hence the correlation is negative for roll rate and positive for roll angle. Further it can be observed that, roll and yaw angle show very good correlation during front braking in a corner. They show very less correlation with steering torque during front braking in a straight line. Yaw and roll rates show better correlation in this condition when compared to yaw and roll angles. During rear braking in a corner, roll angle and yaw rate show positive correlation with respect to steering torque. They also show a positive correlation during rear braking in straight line condition. This study gives an understanding on how steering torque is applied by the rider to stabilize the vehicle during different braking conditions. It also shows how steering torque input is applied by the rider when lateral disturbances are generated due to braking in straight line and cornering.

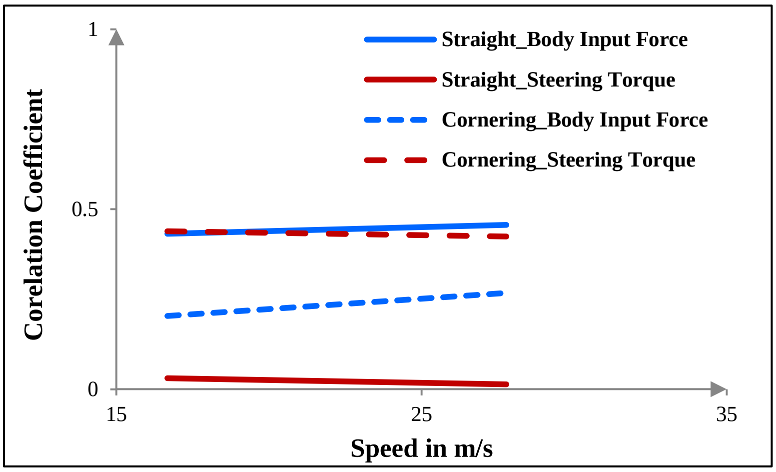

Figure 8: Correlation w.r.t Deceleration - Front Braking

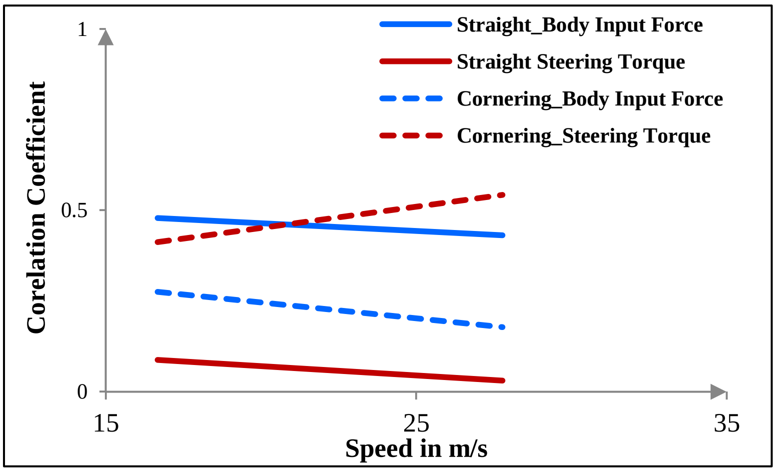

Figure 9: Correlation w.r.t Deceleration – Rear Braking

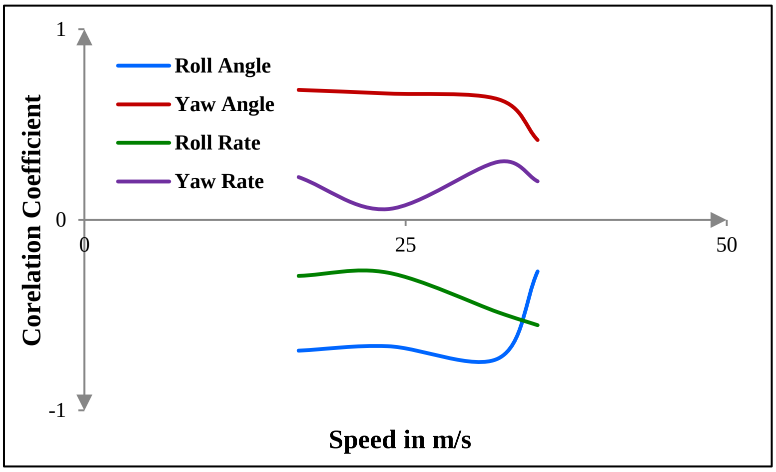

Figure 10: Correlation Results - Front Braking during Cornering

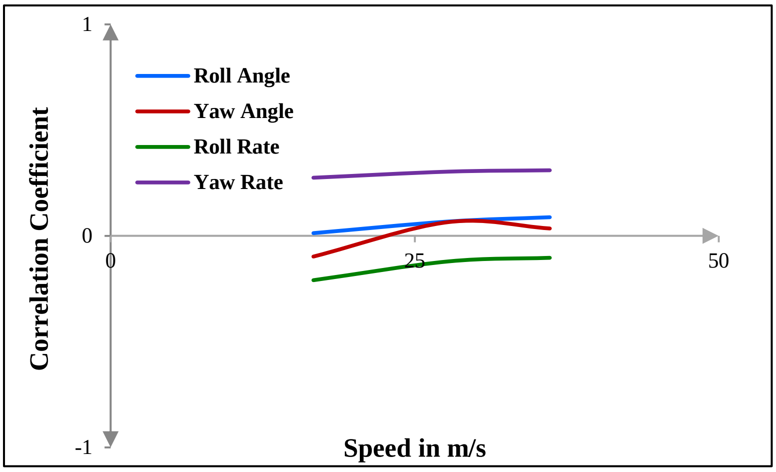

Figure 11: Correlation Results – Front Braking in Straight Line

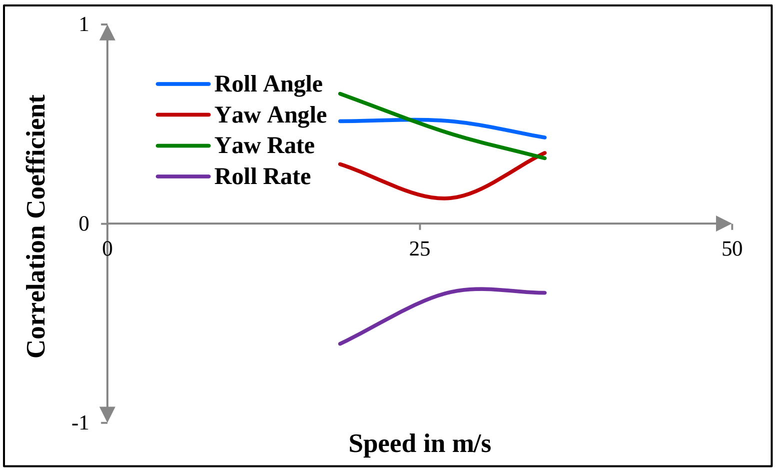

Figure 12: Correlation Results – Rear Braking in Cornering

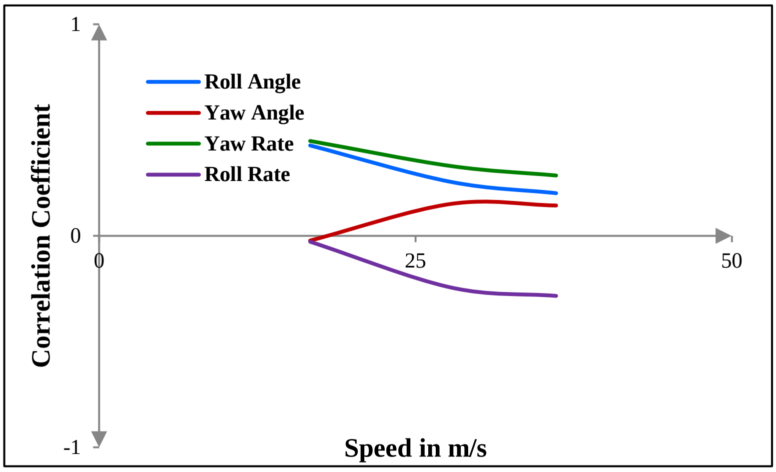

Figure 13: Correlation Results: Rear Braking in Straight Line

4.3 Frequency Analysis of Rider Control Input:

Once the relationship between the steering input given by the rider and lateral disturbances is known, the next step is to understand the frequency at which steering inputs are given by the rider. The measured steering torque input is analysed in the frequency domain and the results are presented in Figures 14, 15, 16 and 17. The results show that the steering torque inputs given by the rider during straight line and cornering braking is less than 5Hz. The amplitude of the steering input given by the rider is relatively small in straight line braking when compared to cornering braking. Between front and rear braking in straight line, the amplitude of the steering input given by the rider is higher during rear braking. However during cornering braking, the amplitudes between front and rear braking are similar. At higher velocities, steering inputs at multiple frequencies are given by the rider during rear braking in corners. During front braking steering input is dominant at frequencies less than 1Hz whereas for rear braking steering inputs are dominant between 0 to 5Hz. Overall the amplitude of the steering torque inputs given by the rider is less than 5Nm and the input frequencies are lesser than 5Hz.

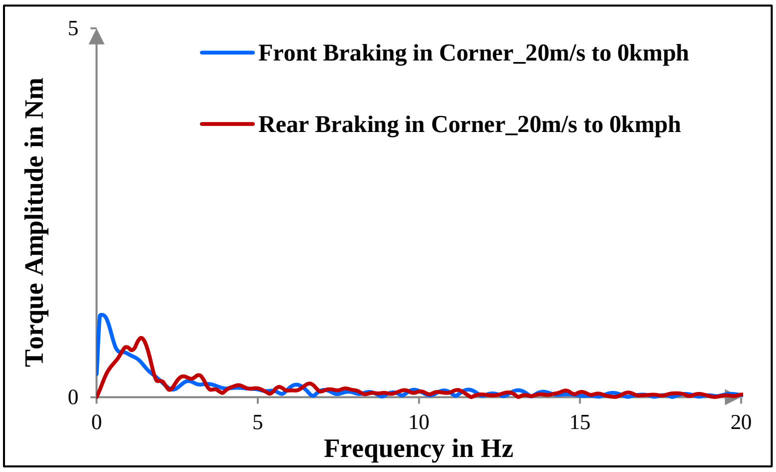

Figure 14: Steering Torque FFT during Front & Rear Braking in Corner

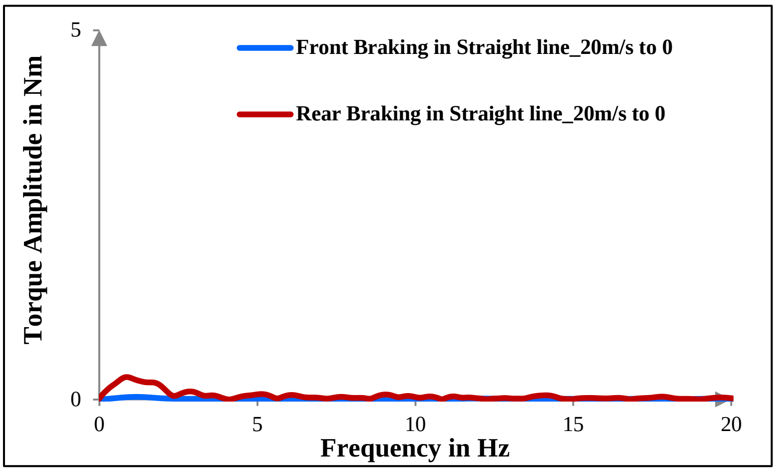

Figure 15: Steering Torque FFT during Front & Rear Braking in Corner

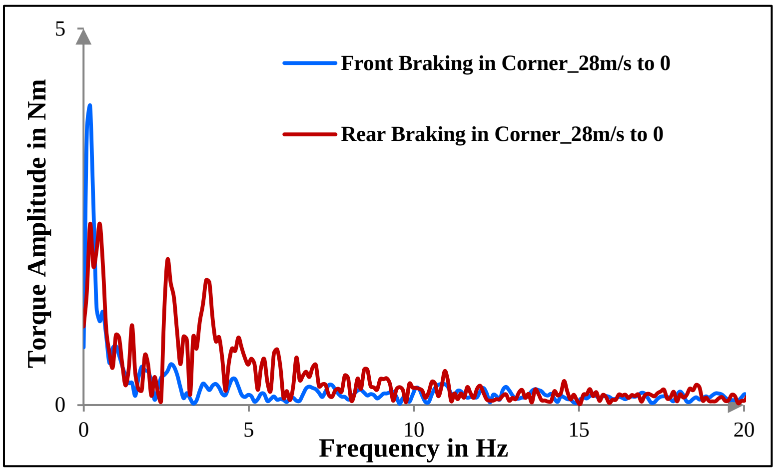

Figure 16: Steering Torque FFT during Front & Rear Braking in Straight Line

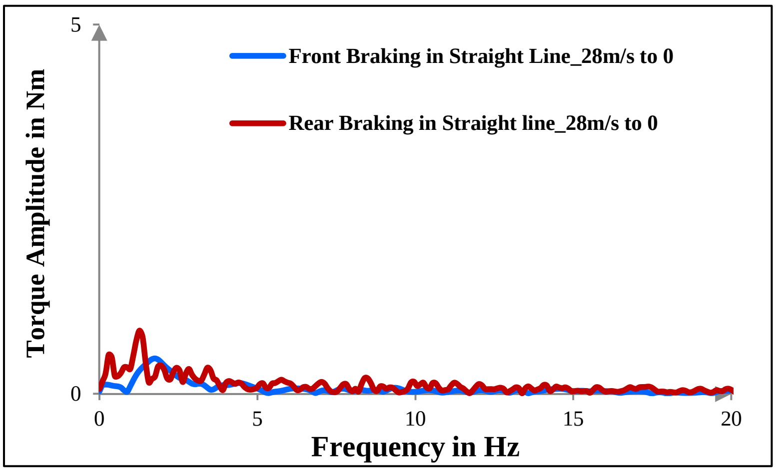

Figure 17: Steering Torque FFT during Front & Rear Braking in Straight Line

4.4 Regression Analysis:

The correlation and frequency analysis of the steering inputs given by the rider show that rider control during straight line and cornering braking depends on the roll and yaw disturbances that are generated. With this understanding, a regression analysis is performed to estimate the relationship of steering torque input given by the rider with roll and yaw oscillations of the vehicle. Linear regression equations are fitted for front and rear braking in straight line and cornering conditions. Steering torque is expressed as a function of roll angle and yaw angle for front braking during corners. It is expressed as a function of yaw rate and roll rate for front braking in straight line. For rear braking in straight line and during cornering, steering torque is expressed as a function of roll angle and yaw rates. The following equations show this relationship.

Front Braking during Cornering:

$$\boldsymbol{T_s(\varphi,\psi) = P0(v) + P1(v) * \varphi + P2(v) * \psi} \tag{1}$$

Front Braking during Straight Line:

$$\boldsymbol{T_s(\dot{\varphi},\dot{\psi}) = Q0(v) + Q1(v) * \dot{\varphi} + Q2(v) * \dot{\psi}} \tag{2}$$

Rear Braking during Straight Line:

$$\boldsymbol{T_s(\varphi,\dot{\psi}) = R0(v) + R1(v) * \varphi + R2(v) * \dot{\psi}} \tag{3}$$

Rear Braking during Cornering:

$$\boldsymbol{T_s(\varphi,\dot{\psi}) = S0(v) + S1(v) * \varphi + S2(v) * \dot{\psi}} \tag{4}$$

Where, φ is the roll angle and ψ is the yaw angle of the motorcycle. $\dot{\varphi}$ and $\dot{\psi}$ are the roll rates and yaw rates of the motorcycle respectively. P (v), Q (v), R (v) and S (v) are the regression coefficients and they depend on the velocity of the motorcycle. These regression coefficients for 2 different velocities are given in Table 1. These equations along with the rider input frequency analysis provides an understanding on how the rider controls the motorcycle during braking in straight line and corners. These results can be further extended to design a control logic that can be used to assist the rider while braking in straight line and corners. Though the results of this study show good statistical accuracy, repeating the same with multiple riders of different skill level and on multiple motorcycles will further improve accuracy. Also, in this study the time delay between steering torque and the lateral disturbances is assumed to be small and neglected. Accuracy can be improved further if time delay is estimated from the test data and used in the analysis. Linear first order equations are estimated to understand the fundamental relationship between steering inputs and the lateral disturbances. The fit accuracy can also be improved if non-linear equations are used to fit the data.

Table 1. Regression Coefficients for different braking conditions

Regression Coefficients	**Velocity in m/s**	**16**	**28**
Front Braking during Cornering	P0	-3.848	-22.63
	P1	-3.473	-6.468
	P2	2.061	-0.1083
Front Braking in Straight Line	Q0	-4.365	0.1857
	Q1	-1.368	0.7829
	Q2	0.1887	1.739
Rear Braking during Cornering	R0	-1.445	-1.478
	R1	-0.1048	2.998
	R2	2.577	1.466
Rear Braking in Straight Line	S0	-4.039	-3.46
	S1	-0.2821	2.878
	S2	1.545	-0.2508

5 CONCLUSIONS:

In this research, a detailed experimental study on the stability and rider control of the motorcycle during braking in a corner is presented. Using MBD simulations and experimental methods, it has been shown that the natural frequency of weave mode is similar in straight line and cornering whereas the damping is increased during cornering. The vibration modes occurring while decelerating the motorcycle in a corner are studied and it is found that these modes occur below 5Hz for both front and rear braking and their amplitudes are higher for rear braking when compared to front braking. It is also found that the frequencies at which the peaks of these modes occur are closer to weave natural frequency.

An experimental approach based on correlations, frequency domain analysis and regression analysis is developed to understand the control of the motorcycle by rider during these instabilities. Using this approach, it is found that,

- The most contributing control input given by the rider while braking in a corner is steering torque and the same during straight line braking are body input forces.
- The frequencies at which the steering inputs are given by the rider to stabilize the lateral disturbances is lesser than 5Hz and their respective amplitudes are higher during rear braking when compared to front braking. These frequencies are similar to those of the vibration modes that occur while decelerating the motorcycle in a corner
- Steering control is better correlated with roll and yaw angle for front braking in a corner and with roll angle and yaw rate during rear braking in a corner. It is better correlated with roll and yaw rates straight line braking when compared to cornering.

- Steering control can be expressed as a function of roll angle and yaw angle for front braking during corners and as a function of yaw rate and roll rate for front braking in straight line. For rear braking in straight line and cornering, it can be expressed as a function of roll angle and yaw rates.

The findings of this research give a detailed understanding on how the rider controls the motorcycle when instabilities due to braking occur. It is shown that these findings can be further used to improve rider control during braking in a corner. As a future work, it is planned to repeat this study with multiple riders of varied skill levels and on multiple motorcycles. It is also planned to extend this study by estimating the time delay between the lateral disturbances and steering torque inputs.

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ANNEXURE

1 Test Motorcycle Specification

S. No	Test Motorcycle Specification	
1	Engine Displacement, *m3*	0.00031
2	Maximum Power, *kW*	25 @ 9700rpm
3	Kerb Weight, *kg*	160
4	Overall Length, *m*	2.001
5	Overall width, *m*	0.786
6	Overall Height, *m*	1.135
7	Wheel Base, *m*	1.36
8	Longitudinal Centre of Gravity from front axle, *m*	0.664
9	Height of Centre of Gravity from ground, *m*	0.528
10	Trail, *m*	0.11
11	Castor Angle, *deg*	0.025

2 MBD Model Details:

For a 70 kg rider and Motorcycle system:			
Parameters	Symbols	Values	Unit
Total mass	M	230.90	kg
Wheelbase	p	1.37	m
Roll inertia at center of gravity	I_g	27	kgm^2
Height of center of gravity from ground	h	0.652	m
Horizontal distance of center of gravity from rear axle	l_r	0.667	m
Caster angle	ε	25.4	degree
Fork offset	d_1	0.003	m
Front steering system mass	M_f	25.88	kg
Height of front steering system center of gravity from ground	h_f	0.479	m
Shortest distance of front steering system CG from steer ax	d	0.012	m
Front wheel radius	r_f	0.293	m
Front wheel spin inertia	I_{fw}	0.375	kgm^2
Rear wheel radius	r_r	0.306	m
Rear wheel spin inertia	I_{rw}	0.425	kgm^2
Acceleration of gravity	g	9.81	m/sec^2