Stability Analysis of Motorcycle by Varying Castor Angle and Trail – A Technical Review

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Abstract— In today’s era where the population of motorcycles has increased highly compared to any other means of routine transportation, hence the steer ability, handling and stability become important aspects designing the vehicle. Motorcycles makeup a complex dynamic system that requires a careful analysis to understand their working and behaviour in varied conditions. The two wheelers are statically unstable and portray more complex behaviour dynamically. The relation of castor angle and trail has proven to be an intricate one yet very pivotal in defining stability of the motorcycle. However, stability is not only dependent on these two factors but also depends on the various other parameters.

Key words: Stability, dynamic system, castor angle, trail

I. INTRODUCTION

The combination of castor and trail has been a compromise between stability and handling. Different types of two wheelers have different demands for being driven varying from a super agile sports motorcycles to highly stable cruiser motorcycles which the daily used commuter vehicles in between the range. But however the range of castor angle and trail remains fixed differently for different kinds of vehicles which has impact on the handling and stability of the motorcycle. The research on the stability of two wheelers started by analysing the bicycles during early 1900s which are the simpler or basic versions of present day motorcycles. Studies ranging from mathematical analysis based on empirical formulae to non-linear computer simulations has been attempted to understand the behaviour of such a complex system in real life.

F.J.W. Whipple et al. (1899) [1] was the first to formally derive the basic bicycle model with the tyres treated to be rigid. He treats the front and rear part symmetrically throughout the derivation. He derived non-linear governing equations and then linearized them about the equilibrium. The linearized equations of a straight running bicycle were in matrix form. Whipple used the Routh-Hurwitz stability criterion to determine the stability regimes of his bicycle and used a non-dimensional analysis, which is helpful when seeking to deduce the way in which the stability properties of a vehicle changes as the geometry is scaled. Whipple’s variable definitions are difficult to decipher, making his paper tedious to read.

Dohring et al (1955) [2] In order to analyse more generally the stability of motorcycles and motor scooters linearized equations for the basic bicycle model by allowing the mass distribution of the front assembly to be fully general. The work focusses on the mass distribution on steer torque with lean as a function. On the front wheel and its impact. Dohring used Newton’s laws to derive the equations of motion in linearized form, rather than linearizing form like Whipple did after deriving the nonlinear equations.

Dohring’s derivation is fairly easy to follow and offers good physical description of the bicycle model. Also Dohring extended the research on real life vehicles like the Vespa scooter and BMW R51/3 and introduced the steering damper effects on the steering. He carried out physical experiments these models to study their stability at different speeds by using stamp pad ink. The results include that a steeper castor angle reduces the magnitude of wobble and weave but at the same time exposes the driver directly to the road conditions and hence the suspension system should act accordingly to overcome stiction and act swiftly.

Digvijai Singh et al. (1964) [3] has shown that the rigidity of the suspension does not affect the stability significantly but the system is more stable than the production models. However the idea presented by Singh proves to be contradictory as the suspension stiffness pays significant role in the motorcycle stability. During acceleration and braking conditions, the suspension compression and expansion cause change in the steering geometry which affects the stability ultimately. He has proposed by changing the moment of inertia of the front wheel, the stability increases at high speed and also at lower speeds on contrary to the usual trend due to the gyroscopic couples of the front wheel. Also there are some obvious outcomes of his research that using a softer wheel at the front tends to decrease the directional stability of the motorcycle. However he had assumed that the side slip is directly proportional to steer angle but that comes out true only for steady state conditions. One of the important points drawn by Singh is the percentage load distribution of the vehicle on the front and rear wheels which is highly stressed in today's motorcycle designing on every front.

Jones D.E.H. et al. (1970) [4] showed that, for the bicycles he tried, both front-wheel spin momentum and positive mechanical trail contributed to self-stability. It was also observed that to balance almost any bicycle that is not self-stable the rider could cause turning of the handlebars appropriately. But when riding without providing any steering control, Jones found it difficult in stabilizing a bicycle whose front-wheel gyroscopic terms are cancelled by an added counter-spinning wheel. His experiments with a variety of bicycles pointed to mechanical trail as another important factor in bicycle stability which influenced the handling of the bicycle. Jones did not do any dynamical modelling, and focused his study only on the trail’s effect calculated the eigenvalues and the speeds at which bicycle lean and steer are self-stable, confirming the century-old result that the conservative system like the bicycle considered can have asymptotic stability.

R S Sharp et al. (1971) [5] derived his set of linearized set of equations of motion for a motorcycle using the Lagarangian approach. The work focusses on the hands off stability of the motorcycles. The model consists of two
frames joined together; the front and the rear which can further bifurcated to the wheel and mass assemblies. The model has many assumptions which simplify the model comparatively. The assumption like the wheels are solid discs and have only point contact with the road thereby eliminating the effect of tyre forces. Also the motorcycle moves through stationary air and hence forces of drag, yaw and roll are small enough to be neglected. The work draws important results like the relation between steering torque and the speed of the vehicle. Also the work shows effects on stability of changing the location of front and rear masses in the system, as the mass at rear frame is lowered it increases the damping of weave mode at all velocities which is an important inference. Majorly it portrays the value of different modes of instability at different velocities in the presence of steering damper. By reducing the front wheel inertia i.e. the gyroscopic effect the need of damping on the steering reduces which is helpful in stabilising the wobble of front wheel. One more important result drawn is that increasing the trail in big amount causes reduction in the instability due to capsizing at low and higher speeds. The works points out at high speed the angle of castor should be increased so as to increase the stability in weave mode or else be compensated by a suitably large trail. 

R S Hand et al. (1988) [6] to understand the self-stability of a bicycle has proposed a bicycle model with four rigid bodies, namely front and rear wheels, rider and rear frame and derived the equations of motions for the same. The equations were derived using the Lagrange’s formula and consists of seventeen independent variables. The work majorly focusses on comparing the previous works on bicycle stability with his own. There is no particular outcome of the research but agrees on the effect of steering angle, tilt, trail and offset of front mass on the wheel had direct impact on the stability of the bicycle. Using the Routh Hurwitz criteria has made the eigenvalues analysis to define the stability of the bicycle. The paper has helped to understand the basics of equations of motion and stability analysis using the eigenvalue analysis method. The study also encompasses how the suggested model can be modified for a motorcycle thought it requires many assumptions to be eliminated to make the system accurate. 

J.M. Papadopoulos et al. (1990) [7] presented the canonical linearized equations of motion for the Whipple bicycle model which consisted of four rigid laterally symmetric ideally hinged parts consisting of: two wheels of front and rear, a frame and a front fork assembly. This conservative non-holonomic system had a seven-dimensional accessible configuration space and three velocity degrees of freedom parameterized by rates of frame lean, steer angle and rear by an added counter-spinning wheel. His experiments with a variety of bicycles pointed to mechanical trail as another important factor in bicycle stability which influenced the handling of the bicycle. Jones did not do any dynamical modelling, and focused his study only on the trail’s effect calculated the eigenvalues and the speeds at which bicycle lean and steer are self-stable, confirming the century-old result that the conservative system like the bicycle considered can have asymptotic stability. 

Hsien-Chung Lai, Jing-Sin Liu, D.T. Lee et al. (2000) [8] have made a detailed study on the stability of the electrical motorcycle as the electrical motorcycles are not the same as conventional motorcycles in many aspects like the forward speed, design considerations and control. The equations of motion for lateral conditions for an electrical motorcycle, which include the rider upper body leaning motion during negotiating a curve, are derived from Newtonian mechanics. By associating transfer functions at various speeds, perception of riding comfort is defined as the damping ratio of frequency domain Bode plots in classical control theory. The perception of riding comfort is issue for changing mass centre position, total weight of the motorcycle, the wheelbase, the front fork rake angle and the front wheel trail distance of the motorcycle. On the premise of the stability, the use of maximum damping ratio is done to represent the riding response of the motorcycle to find the best perception of riding comfort. By the analysis, following results are surfaced; the movement the mass center forward, shortening the wheelbase, steepening the front fork rake angle and shortening the front wheel trail distance of the design of electrical motorcycles in the market, a better perception of riding comfort can be achieved. 

R. S. Sharp and D. J. N. Limebeer et al. (2004) [9] have developed and presented an extended model consisting of motorcycle and the rider to include the yaw freedom of the upper body of the rider. Also in this model the tire model is borrowed from H B Pacejka, “the magic formula” tire model. They have applied the research on two kinds of tyre configuration. The work also describes the effect of rigid and flexible frames i.e. a flexible frame can digest the wobble but for a rigid frame the steering damper is highly inevitable. The work gives an improved understanding of steering wobble oscillations of motorcycles through simulation by introducing a model for mono suspension used in the rear of the motorcycle. The study shows that the rider upper body plays a pivotal role in balancing the wobble implying that a lean driver is more prone to wobble instability compared to a heavier one. Emphasis is also placed on relationships between natural frequencies and the consequent possibility of internal and combination resonances, and advantageous alternatives to the conventional steering damper for restraining the steering system. 

Vittore Cossalter et al. (2002) [10] here presented an eleven degrees of freedom, non-linear, multi-body dynamics model of a motorcycle. Front and rear chassis, steering system, suspensions, tires and a rigid rider are the main elements of the model. This model also describes the dynamic behaviour of tires in a way similar to relaxation models but by considering the deformation of the carcass w.r.t. to the rim. Equations of motion stem from the natural coordinates approach which reduces the amount of complexities involved but however increases the number of equations by a big amount. The equations are solved using a equations likely to naturally reduce the roll angle. Also the study explains how at some point on negotiating a curve if the brakes using the front brake, as a consequence to it the new equilibrium steering torque is much more misaligning, experiments were carried on an equipped motorcycle for If the rider does not promptly adapt his handlebar torque, the vehicle remains no more in equilibrium and the steer angle increases due to the excess of misaligning torque.
Simos Evangelou et al. (2004) [11] by using a multibody simulation software AUTOSIM developed the nonlinear model based on the equations developed by R. S. Sharp in 1971. Also he has developed a linear model using the MATLAB to create space time models. The free steering system of a motorcycle is essential to its stability and controllability. Those motorcycle design features that determine the self-steering of the machine are crucial to determining the stability properties. Steering torques needed for steady turning are normally very small but they are much larger often for transient manoeuvring. Linear stability and small perturbation responses are made complex by the large number of conditions in which a motorcycle runs, by the large number of design parameters involved and by the interactive nature of those design parameters. The study shows the damping of the wobble mode is substantially increased when the machine is ascending an incline at constant speed, or accelerating on a level surface. Except at very low speeds, inclines, acceleration and deceleration appear to have little effect on the damping or frequency of the weave mode. By extensive use of both the linear and non-linear models the effect of acceleration and braking on the stability of the motorcycle. It has also been shown that light riders are more likely to suffer from road forced resonant weave oscillations than are heavy ones.

R. P. Rajvardhan et al. (2010) [12] have verified through analysis of a SUV modelled and tested on ADAMS/Car that increasing positive caster angle increases the mechanical trail, and this trail increases the self-aligning torque which improves the steering wheel return ability. They have created a multibody model of Honda CRV and simulated the results for various wheels geometry parameters. As the self-aligning torque acts in the direction opposite to the steering torque, the steering effort of the driver increases. The important result of the study is that increase in the caster angle increases the return ability but at the same time also increases the steering effort. Negative caster angle reduces the steering effort due to the absence of sufficient aligning torque, but it leads to the wheel wandering problem. Effects of providing positive and negative camber are also identified in addition to toe in and toe out conditions. They have come up with a steering configuration different to the manufacturer’s configuration which proves to be more stable theoretically.

V. Cossalter et al. (2010) [13] has addressed the decomposition of the motorcycle steering torque in its main components. The work shows that the steering torque applied by the rider on the handlebar is the reaction to many contributes such as road-tyre forces, gyroscopic torques, centrifugal and gravity effects. The equations of motion in moving frame are derived with the Newton-Euler approach for each of the considered bodies. The steering torque components are analysed in steady cornering condition, i.e. at constant speed and constant road curvature, i.e. at constant roll angle and lateral acceleration. The analysis also explains why when braking on curve the vehicle is Equations of motion stem from the natural coordinates approach which reduces the amount of complexities involved but however increases the number of equations by a big amount. The equations are solved using a equations likely to naturally reduce the roll angle. Also the study explains how at some point on negotiating a curve if the brakes using the front brake, as a consequence to it the new equilibrium steering torque is much more misaligning, experiments were carried on an equipped motorcycle for If the rider does not promptly adapt his handlebar torque, the vehicle remains no more in equilibrium and the steer angle increases due to the excess of misaligning torque.

W. Ooms Bsc. et al (2011) [14] has derived an 11 degree of freedom motorcycle model that predicts the dynamic behaviour of a motorcycle. Though the model consists of only eleven degrees of freedom it is sufficient to describe the conditions of the vehicle in most cases. The method of deriving the equations of motion is borrowed from robot modelling and starts with defining the important parameters and generalized coordinates. The equations of motion are implemented in a Simulink model and simulated. The study focusses on developing rider less motorcycle employing a controller. The controller develops is of proportional type but however, a PID controller could be used which has better results and relates to actual life conditions. Appropriate sensors are suggested to record date for actuations of steering axis, throttle and braking and supplying the information to an ECU which in accordance to the algorithm takes predefined steps which are indicated for the experimental validation of the idea.

II. CONCLUSIONS

The study carries out so far gives a insight towards the geometry of motorcycle the steering and the fundamentals of vehicle dynamics. The review shows how the motorcycle model can be created and used for analysis of a dynamic system. So far very limited research has been done in the field of motorcycle dynamics which indicates the scope of research in the field under various heads. Hence the review carried out helped in learning the importance of certain parameters in steering system and their effect on stability. Some of the vital findings of the review work done can be summarised as below:

1) A clear definition about stability in terms of a two wheeler is obtained.
2) Castor and trail play a pivotal role in defining the steerability, handling and stability of the overall system.
3) The relations of castor and trail and its effect on the handling are found.
4) Creating the multibody model for the system requires intense mathematical expertise.
5) The model of eleven degree of freedom is the only designed and validated so far which describes the condition of the system near to real life, also the limitations for the same are realised.
6) Knowledge about various software which can be used in the calculations and simulation of the system.

REFERENCES

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