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Low end Motorcycle Front brake Lever travel and Braking torque analysis

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Abstract— The Motorcycles in India uses split type foundation brakes where the hand operated control force of the rider is used to initiate front wheel braking. In the motorcycles employed with hydraulic disc brakes, the control force is converted into braking torque at the brake disc and is used to slow down the vehicle or to bring it to a complete halt. During a panic braking event, the perception time is very short and calls for quick braking action and short stopping distance. These objectives can be performed by targeting lever travel to achieve quick braking action and augmenting braking torque pertaining to attain shorter stopping distance. The work presents physical process of motorcycle front braking in the form of validated mathematical equations that has common variables. These variables can be targeted to achieve multi-objective optimization of disc brakes that corresponds to quick braking action and reduced stopping distance simultaneously.

Index Terms— Motorcycles, Disc brakes, Lever travel equation, Rider's perction, Panic braking, Control force, Braking torque, Stopping distance

NOTATIONS

$F_{control}$	Control Force	N
$F_{chamber}$	Chamber Force	N
b	Distance between lever mounting point and ball centre	mm
c	Distance between lever mounting point and actuation point	mm
Δx_s	Small incremental stroke on lever	mm
Δy_s	Small incremental stroke on master cylinder piston	mm
Δx_{mh}	Lever travel required to close microhole	mm
Δx_{ve}	Lever travel required to overcome volumetric expansion	mm
Δx_{rb}	Lever travel required to overcome rollback	mm
Δx_{pc}	Lever travel required to overcome pad clearance	mm
a	Distance between lip of primary seal and closure of micro hole	mm
V_{exp}	Volumetric expansion of brake hose pipe	cc/m
h	Length of the brake hose pipe	mm
Q_s	Volume of fluid discharge resulting from small stroke on lever	mm^3
Q_{rb}	Volume of fluid discharge to overcome rollback	mm^3
Q_{pc}	Volume of fluid discharge to overcome pad clearance	mm^3
d_{mc}	Diameter of master cylinder piston	mm
d_c	Diameter of calliper piston	mm
n_{mp}	Number of master cylinder piston	
n_{cp}	Number of calliper piston	
L_{rb}	Rollback length	mm
L_{pc}	Pad clearance length	mm
A_{mc}	Area of master cylinder piston	mm^2
A_c	Area of calliper piston	mm^2
P_{line}	Line pressure	MPa
n_p	Number of brake pads	
T_b	Braking torque at the front wheel	Nm
R_c	Effective radius of the calliper	m
μ	Coefficient of friction between brake pads and brake disc	

1 INTRODUCTION AND GROUNDWORK

MOTORCYCLE braking is one of the important phenomena that ensures safety of the rider and the motorcycle.

The control force applied by the motorcycle rider on the control device (front brake lever in case of hand operated front wheel brakes) of a motorcycle creates line pressure between the master cylinder and the calliper. This control force is augmented and acts at the calliper piston that makes it to move forward. Brake pads attached to this calliper pistons are pushed against rotating disc and a braking torque is introduced. As a result, braking force is developed that makes the vehicle to decelerate or to stop completely. In India, people choose motorcycles for everyday commuting. Transportation is the primary concern while designing motorcycles in India. People scrutinize for parameters such as Power, Price, Mileage, Cost, Spare cost, Vehicle life etc. [12]. Also the geometry of Indian motorcycles is very much different from that manufactured in other countries such as USA, Germany, Italy, and Japan etc. The Low end motorcycles forming large cluster in India is characterised by smaller wheelbase and high centre of gravity. High end motorcycles are equipped either with combined brake system (CBS) or Antilock braking system (ABS) to achieve effective braking without wheel lock. Though Government of India has made ABS mandatory by the year 2018, it can be seen that the incorporation on ABS and CBS are still in infant stage for a low end motorcycle in India. This makes a Non ABS split type foundation brakes as primary brakes in low end motorcycles. During braking, front wheel brakes aids in achieving reduced stopping distance effectively due to load transfer effect and optimal braking [6]. During the deceleration phase, the load on the front wheel increases, while the load on the rear wheel decreases, due to the load transfer effect [5][13]. Also In two wheelers, rear wheel braking is of little use on optimal roads with high coefficient of friction and it is not good idea to use rear braking force greater than front one, since optimal braking line plotted for

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front tyre brake force coefficient as ordinate and rear tyre brake force coefficient as abscissa does not intersect the curve when force distribution is higher at rear [5]. However rider fails to notice the importance of front braking in achieving shorter stopping distance during panic braking event. Concept of rider's perception is stressed to understand the behaviour of rider during panic braking event [8][11]. Perception time being very short calls for quick braking action and shorter stopping distance. Seating position adds the major part to it as the rider during a collision avoidance event applies rear brakes first since it is quickly available, whereas the rider has to apply front brakes by unwrapping and stretching the fingers beyond brake lever and then pulling it thus making him to think in delay of braking cycle [11]. This may cause swerving of motorcycle due to rear wheel lock making it to lose directional control. It is to be noted that the pilot fatigue hampers the concept of prepositioning fingers all the time. Previous works already concluded that the improper braking method is the main reason for injuries of rider and fatal accidents [1]. Thus it is necessary to modify within the front braking system of a motorcycle that builds the confidence in rider pertaining to quick baking action and smaller stopping distance when the front brakes are applied. Lever travel is one such parameter that can be targeted to achieving quick braking action. Augmenting the braking torque at the disc makes the motorcycle to attain shorter stopping distance. Foregrounding these factors, this paper presents the work on a hydraulic front brake system of a low end motorcycle, wherein the validated mathematical equations developed for lever travel and braking torque can be used for multi objective optimization to achieve quick braking action and shorter stopping distance simultaneously.

2 Description of Front Brake System

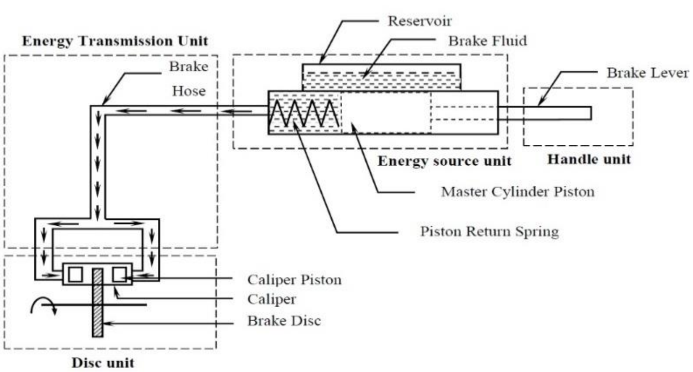

Fig. 1. Outline of a hydraulic front brake system employed in motorcycle

The braking system of a motorcycle is classified as Energy Source, Apply system and Energy transmission system [10]. Front brake system of a low end motorcycle is primarily made of four units namely Handle unit, Energy source unit, Energy transmission unit and Disc unit. Handle unit of a front braking has a control device called as brake lever. The energy source unit has a master cylinder that houses master cylinder piston subassembly and an incompressible brake fluid. Brake hoses along with its sub components that connects master cylinder and calliper makes Energy transmission unit. Calliper sub assembly that has child parts of brake calliper and a brake disc forms the disc unit [10]. The Brake lever is fitted to Master cylinder at lever mounting point and is facilitated to rotate about its axis. This operation makes it a bell crank mechanism where the vector quantities of force is changed.

The control force applied on brake lever is multiplied at the chamber of master cylinder with the concept of mechanical advantage. This force pushes the master cylinder piston creating constant line pressure and initiates braking action. The brake fluid present in front of master cylinder piston is forced to travel towards calliper through brake hose. The further augmented-force developed at calliper piston makes the brake pads to rub against brake disc thus establishing friction. The action results in development of braking torque that aids to achieve deceleration of motorcycle.

3 Motorcycle Front Braking Kinetics

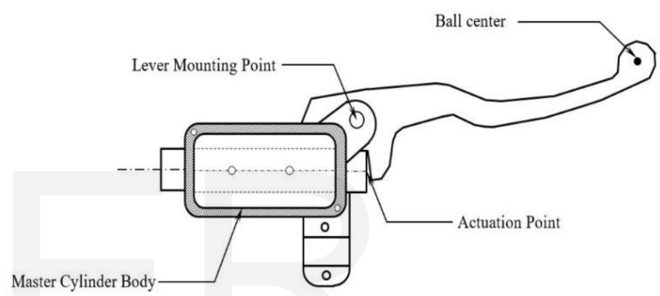

Fig. 2. Motorcycle front braking control device

The Figure 2 represents the typical motorcycle front brake control device employed in low end motorcycles.The control device (Brake lever in this case) is coupled to master cylinder body at the lever mounting point.

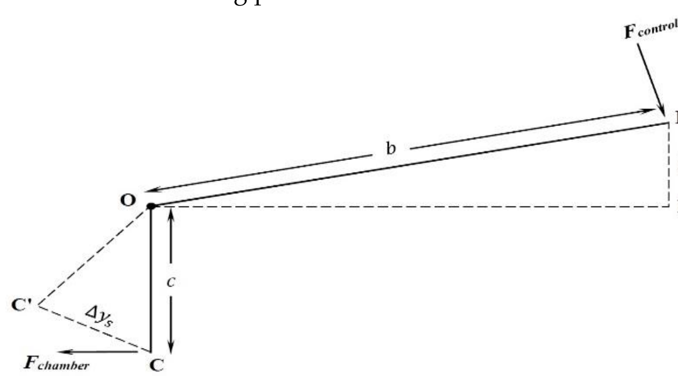

Fig. 3. Freebody diagram of the motorcycle front braking control device

The Figure 3 represents the freebody diagram of the same. Referring to FBD of the control device and applying the law of lever to it, we get

$$\frac{F_{chamber}}{F_{control}} = \frac{b}{c} \quad (1)$$

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Also, work done is the product of force and displacement. Thus by equating work done to move lever using the control force to get output of chamber force at actuation point to initiate master cylinder piston movement, we get

$$\frac{F_{chamber}}{F_{control}} = \frac{\Delta x_s}{\Delta y_s} \quad (2)$$

Now, by equating (1) and (2), we get

$$\frac{F_{chamber}}{F_{control}} = \frac{\Delta x_s}{\Delta y_s} = \frac{b}{c} \quad (3)$$

From the above equation (Equation 3), it is concluded that the ratio of lever travel to master cylinder piston travel and the ratio of the lengths of control device are same as mechanical advantage of the brake lever.

3 Mathematical model of the front brake lever travel

The total lever travel of the hydraulic front brake system X is the sum of four major discretised parameters. These are developed using the concepts of engineering and are explained in this section.

3.1 Lever travel required to close micro hole

To build the line pressure in the system, the primary seal of the master cylinder piston has to close the micro hole located ahead of it.

Thus for small lever travel of Δx_s, the master cylinder piston moves a distance of Δy_s. Then for the master cylinder piston to travel 'a' distance to close micro hole, lever travel Δx_{mh} required will be

$$\Delta x_{mh} = \frac{\Delta x_s}{\Delta y_s} * a \quad (4)$$

3.2 Lever travel required to overcome volumetric expansion of brake hose

The line pressure developed causes the volumetric expansion [2] of brake hose. This requires the filling of additional brake fluid to maintain constant line pressure during braking. The discharge of the brake fluid is product of area of master cylinder piston and length of travel.

Let Δx_s be small lever travel causing discharge of Q_s volume of fluid and resulting in master cylinder piston movement of a distance of Δy_s . Then to overcome volumetric expansion V_{exp} over the total length of hose pipe h, lever travel required Δx_{ve} is given by

$$\Delta x_{ve} = \frac{V_{exp} * h}{Q_s} * \Delta x_s \quad (5)$$

$$\Delta x_{ve} = \frac{V_{exp} * h}{n_{mp} * \frac{\pi}{4} * {d_{mc}}^2 * \Delta y_s} * \Delta x_s \quad (6)$$

$$\Delta x_{ve} = \frac{4 * V_{exp} * h}{n_{mp} * \pi * {d_{mc}}^2} * \frac{\Delta x_s}{\Delta y_s} \quad (7)$$

3.3 Lever travel required to overcome caliper rollback

For effective braking of motorcycle, the calliper pistons has to overcome rollback length.

Let L_{rb} be the distance travelled by calliper pistons to overcome rollback. The volume of fluid Q_{rb} required to overcome rollback is product of area of calliper pistons and rollback length.

Let Δx_s be small lever travel causing discharge of Q_s volume of fluid resulting in master cylinder piston movement of a distance of Δy_s . Then to overcome rollback effect by discharging Q_r volume of fluid, lever travel required Δx_{rb} is given by

$$\Delta x_{rb} = \frac{Q_{rb}}{Q_s} * \Delta x_s \quad (8)$$

$$\Delta x_{rb} = \frac{n_{cp} * {d_c}^2 * L_{rb}}{n_{mp} * {d_{mc}}^2} * \frac{\Delta x_s}{\Delta y_s} \quad (9)$$

3.4 Lever travel required to overcome pad clearance

The brake pads get clamped to brake disc initiates braking torque due to friction generated between them. However the clearance between two parallel surfaces is inherent due to various factors such as manufacturing defects, geometric tolerances, surface irregularities etc. Considering all the above factors it is essential to overcome pad clearance completely for effective braking.

Thus by deriving on similar lines for a floating type calliper assembly, Let L_{pc} be the distance travelled by calliper pistons to overcome pad clearance. The volume of fluid Q_{pc} required to overcome pad clearance is product of area of calliper pistons and clearance length.

Let Δx_s be small lever travel causing discharge of Q_s volume of fluid resulting in master cylinder piston movement of a distance of Δy_s . Then to overcome pad clearance by discharging Q_{pc} volume of fluid, lever travel required Δx_{pc} is given by

$$\Delta x_{pc} = \frac{Q_{pc}}{Q_s} * \Delta x_s \quad (10)$$

$$\Delta x_{pc} = \frac{n_{cp} * {d_c}^2 * L_{pc}}{n_{mp} * {d_{mc}}^2} * \frac{\Delta x_s}{\Delta y_s} \quad (11)$$

Now the total lever travel of the system is the summation of the equation (4) (7) (9) and (11).

Thus by substituting and re arranging, final equation for total lever travel of the hydraulic front brake system is given by expression

$$X = \Delta x_{mh} + \Delta x_{ve} + \Delta x_{rb} + \Delta x_{pc}$$

$$\Rightarrow$$

$$X = \left(\frac{\Delta x_s}{\Delta y_s} * a\right) + \left(\frac{4 * V_{exp} * h}{n_{mp} * \pi * {d_{mc}}^2} * \frac{\Delta x_s}{\Delta y_s}\right) + \left(\frac{n_{cp} * {d_c}^2 * L_{rb}}{n_{mp} * {d_{mc}}^2} * \frac{\Delta x_s}{\Delta y_s}\right) + \left(\frac{n_{cp} * {d_c}^2 * L_{pc}}{n_{mp} * {d_{mc}}^2} * \frac{\Delta x_s}{\Delta y_s}\right)$$

$$\Rightarrow$$

$$\boldsymbol{X = \left(\frac{\Delta x_s}{\Delta y_s}\right)\left[(a) + \left(\frac{1}{n_{mp}{d_{mc}}^2}\left\{\left(\frac{4hV_{exp}}{\pi}\right) + n_{cp}{d_c}^2(L_{rb} + L_{pc})\right\}\right)\right]} \quad \mathbf{(12)}$$

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4 Mathematical model of the braking torque developed due to front wheel braking of motorcycle

Let T_{b_f} be the total braking torque developed at the front wheel of motorcycle and R_c be the effective radius of calliper pistons and µ be the coefficient of friction between pads and the brake disc. Then Braking torque developed at the front wheels is given as

$$T_b = n_p * \mu * R_c * F_c \quad (13)$$

But the calliper force F_c acting on the calliper pistons is the product of line pressure P_{line} and area of calliper pistons A_c. Thus substituting these in the equation (13), we get

$$T_b = n_p * \mu * R_c * P_{line} * A_c \quad (14)$$

The line pressure developed in the system is the result of chamber force $F_{chamber}$ acting per unit area of master cylinder piston A_{mc}. Thus substituting for P_{line} on similar lines, we get

$$T_b = n_p * \mu * R_c * \frac{F_{chamber}}{A_{mc}} * A_c \quad (15)$$

Expressing areas A_c and A_{mc} as a function of diameter of caliper piston d_c and diameter of master cylinder piston d_{mc} respectively, the equation (15) can be rewritten as

$$T_b = n_p * \mu * R_c * \frac{F_{chamber}}{n_{mp} * {d_{mc}}^2} * n_{cp} * {d_c}^2 \quad (16)$$

Rewriting equation (16) by substituting for $F_{chamber}$ from equation (3), we get

$$T_b = n_p * \mu * R_c * \frac{F_{control} * \frac{\Delta x_s}{\Delta y_s}}{n_{mp} * {d_{mc}}^2} * n_{cp} * {d_c}^2 \quad (17)$$

$$T_b = n_p * \mu * R_c * \frac{F_{control}}{n_{mp} * {d_{mc}}^2} * n_{cp} * {d_c}^2 * \frac{\Delta x_s}{\Delta y_s} \quad (18)$$

$$\boldsymbol{T_b} = \left(\frac{\Delta \boldsymbol{x_s}}{\Delta \boldsymbol{y_s}}\right)\left(\frac{\boldsymbol{d_c}^2}{\boldsymbol{d_{mc}}^2}\right)\left(\frac{\boldsymbol{n_p} * \boldsymbol{n_{cp}}}{\boldsymbol{n_{mp}}}\right)(\mu * \boldsymbol{R_c} * \boldsymbol{F_{control}}) \quad \textbf{(19)}$$

5 Validation of the mathematical equation

The mathematical equations developed for front brake lever travel and the front braking torque is tested for its validation on a front braking system of a commercial low end motorcycle. The numerical data corresponding to variables present in the equations is collected from the brake manufacturer.

The part drawings of the child parts of the brake system assembly were critically analysed and the data is fed to the equation to get the theoretical values of lever travel and the braking torque.

The Table 1 shows the results of theoratical lever travel and braking torque for the control forces ranging from 5 Kgf to 20 Kgf [4].

TABLE 1
THEORATICAL LEVER TRAVEL AND BRAKING TORQUE

Control force (Kgf)	Lever travel (mm)		Braking torque (Nm)
	Min	Max	
5	39.65	59.97	214.14
6	41.16	61.61	256.97
8	42.67	63.24	342.62
10	46.07	67.01	428.28
12	48.26	69.28	513.93
14	49.66	70.78	599.59
16	52.31	73.55	685.24
18	55.15	76.98	770.90
20	57.11	78.84	856.55

A brake inertial dynamometer [3] is used for the experimentation. Load cell is used to apply the control force on the brake lever. For control force varying from 5 Kgf to 20 Kgf corresponding braking torque and lever travel is measured. The Table 2 shows the experimental results of lever travel and braking torque developed.

TABLE 2
LEVER TRAVEL AND BRAKING TORQUE (EXPERIMENTAL)

Control force (Kgf)	Lever travel (mm)	Braking torque (Nm)
5	42.13	202.65
6	45.08	244.89
8	49.30	326.87
10	54.81	409.17
12	59.47	491.78
14	63.63	573.62
16	67.48	653.73
18	72.74	734.34
20	76.82	823.08

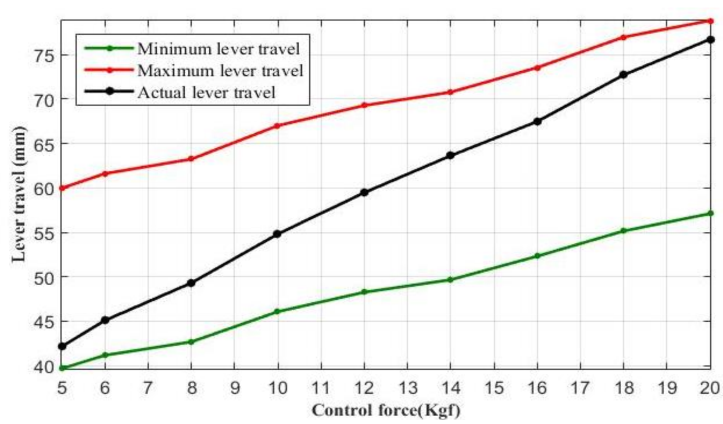

Fig. 4. Lever travel vs. Control force

The Figure 4 shows the graph of experimental and theoretical lever travel plotted against the control forces. It is clear that the lever travel of the braking system is not undershooting or overshooting the minimum and maximum possible limits of lever travel respectively thus validating the lever travel equation.

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But as the control force increase, lever travel increases correspondingly and tend to reach maximum limit. This can be explained using the concept of volumetric expansion and the line pressure losses. The medium expansion hoses are designed to permit maximum expansion of around 5 - 8% of its minimum expansion value that accounts for the possible lever travel. Thus the line pressure developed may expand the brake hose pipe beyond the minimum limit and the system losses such as mechanical losses and hydraulic losses adds to it and justifies the result

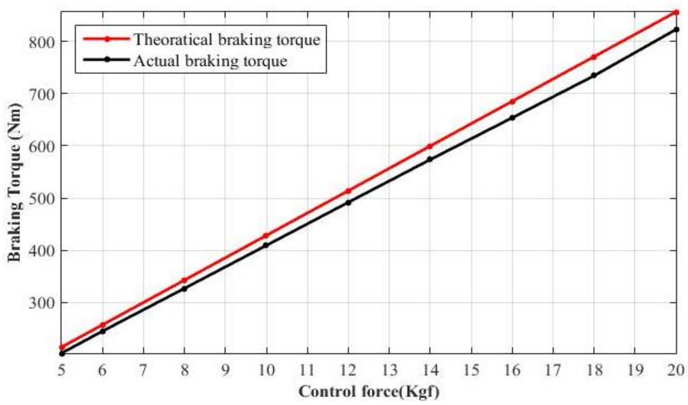

Fig. 5. Braking torque vs. Control force

The Figure 5 shows the graphical comparison between theoretically calculated and experimentally tested braking torque against control force ranging from 5 Kgf – 20 Kgf. It can be seen that the actual braking torque is lesser than that of the theoretically estimated. This is accounted from the system losses during line pressure build up which hampers the braking efficiency.

5 Conclusion and Future Work

It is deduced that the theoretical results very much matches with the experimentally tested results. Thus the mathematical equations developed for the front brake lever travel and the front braking is valid.

The equations of lever travel and braking torque has five common variables between them namely Mechanical advantage, Diameter of master cylinder piston, Diameter of calliper piston, Number of master cylinder piston and Number of calliper piston. These can be established as design variables and serves for multi-objective optimization to achieve quick braking action and shorter stopping distance simultaneously.

The work can be extended on similar lines to combined braking system (CBS) by critical analysis of the same. The optimization of every independent variable present in the equation is also possible and forms the future scope of this work.

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