DEVELOPMENT AND OPTIMIZATION OF MR FLUID DISK BRAKE MODEL

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Abstract -*This research paper aims to develop a Magneto-Rheological Fluid Brake (MRB) model in conjunction with an Anti-Lock Braking System (ABS) that showcases better performance than Conventional Hydraulic Brakes (CHB). This proposed MRB system is then compared with the CHB model. The MRB system integrates mechanical and electronic components with MR fluid, enabling more efficient and reliable braking actuation. A quarter-vehicle model integrated with a sliding mode controller is utilized to maintain optimal traction between tires and road to avoid tire locking. However, during the implementation of the sliding mode controller, occurrence of chattering, a detrimental effect, is observed. To mitigate this issue, a saturation function is applied. Finally, a more effective eradication of chattering is achieved by developing a time-varying saturation boundary layer across the switching surface. The results demonstrate significant improvements in braking performance and offer valuable insights for future advancements in automotive brake systems*

Key Words: Magneto-rheological, Anti-Lock Braking system, Sliding Mode Controller, Quarter Vehicle Model

1.INTRODUCTION

1.1 Conventional Hydraulic Brakes

Working: Conventional hydraulic brakes use an arrangement of brake pedal which is connected to a circuit(hydraulic). First brake pedal has to be pressed which impels the fluid into the master cylinder that results in pressure that pushes brake shoes against the wheels which causes braking torque to be generated because of friction [1].

Applications: CHB is commonly used in modern commercial vehicles. It is also used widely in conjunction with various other technologies like ABS, regenerative breaking, Vehicle Cruise Control etc.

Limitations: Although popular, the CHB systems do have several limitations which are discussed in the following lines. Brake fluid under unfavorable conditions are found to be leaking, thereby leaching into soil and water bodies, and hence becoming detrimental to the environment. They are bulky in size whose installation and maintenance is challenging. The pads used in brakes wear out over time and need to be replaced regularly, which causes inconvenience and is expensive. These systems have a certain amount of delay in their response time, which can affect the effectiveness and precision of braking actions. This delay can lead to longer stopping distances and reduced control during critical situations [2].

1.2 Magneto-Rheological Fluid Brakes

1.2.1 MR fluids

MR fluid is a smart material whose rheological characteristics change under the influence of magnetic field. The fluid is produced by mixing micron-sized iron or particles of carbonyl to carrier fluid such as oil or water and silicon. When the fluid is subjected to a magnetic field, the state of the substance changes from a fluid to a viscoelastic solid. The particles of iron particles obtain a dipole moment under the influence of magnetic field to form linear chains parallel to the direction of the magnetic field. Therefore MR fluid has a controllable yield strength that directly depends upon the magnitude of the applied magnetic field [3].

1.2.1 MR fluids

MRB is a friction-based braking system. In this braking system, the magneto-rheological fluid is filled between the rotor and stator as shown in Figure 1. Since the fluid has controllable rheological properties which helps to produce shear force thus generating braking torque. When current flows through the coil, a magnetic field is generated which converts the magneto-rheological fluid in the gap into a solid-like substance immediately. It is a reversible process, when the current flow through the coil stops, the applied magnetic field also stops which allows the MR fluid to return to its liquid state [4].

The MRB has many advantages over CHB such as:

- Better control and near instantaneous response time
- Since MRB doesn't utilize the friction generated between the brake pads and rotor to slow down the car, thus significantly reducing the wear and tear between components. Hence longer service life and less maintenance

- MRB has better energy efficiency since it generates less heat during the braking operation
- Easy integration with other electronic components of the vehicle

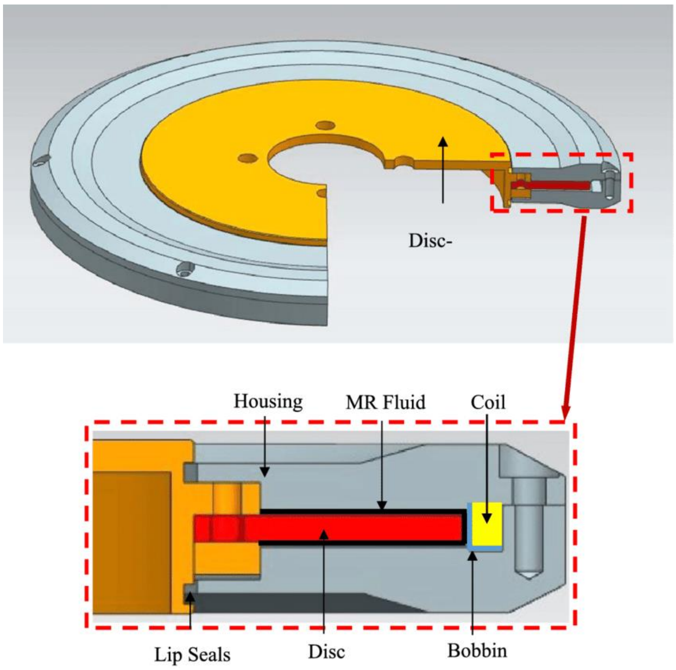


Fig -1:MRB Model [5]

2. Methodology

The research aims to optimize the MR fluid brake model and conduct a comparative analysis with the conventional hydraulic brake model, thereby providing insights into the potential advantages of MR fluid brakes in braking applications.

1. CHB Model construction: Model of CHB in conjunction with ABS is developed. The model utilizes vehicle dynamics and uses the Bang-Bang controller to maintain optimal slip-ratio.
2. MRB Model and optimization: Model of MRB is developed using the quarter vehicle model which utilizes the sliding mode controller to keep a constant value of the slip ratio.
3. Comparative Analysis: Using the MATLAB models of the two braking systems, Comparative analysis will be performed on the following parameters:
    - 3.1. Stopping time
    - 3.2. Stopping distance
    - 3.3. Integral Squared Error (ISE)
    - 3.4. Integral Time-weighted Absolute Error (ITAE)

3. Computational Modeling and Comparative Analysis of MRB and CHB

Table -1: Parameters of the Vehicle

Wheel radius, R_w	0.326 m
Wheel base, l	2.5 m
height of the point of center of gravity, h_{cg}	0.5 m
Wheel mass, m_w	40 Kg
Quarter vehicle mass, $\frac{1}{4}m_v$	415 Kg

3.1 Modeling of CHB and ABS

Table -2: Parameters pertaining to hydraulic brakes

number of friction surfaces, n	2
Drag Coefficient C_d	0.539
Projected Area	2.04 m^2
Max pressure	20 x 10^6 Nm^{-2}
Disc brake Coefficient of friction	0.34

The model is created utilizing an earlier study [6], following results are obtained:

Chart -1: Vehicle speed and wheel speed

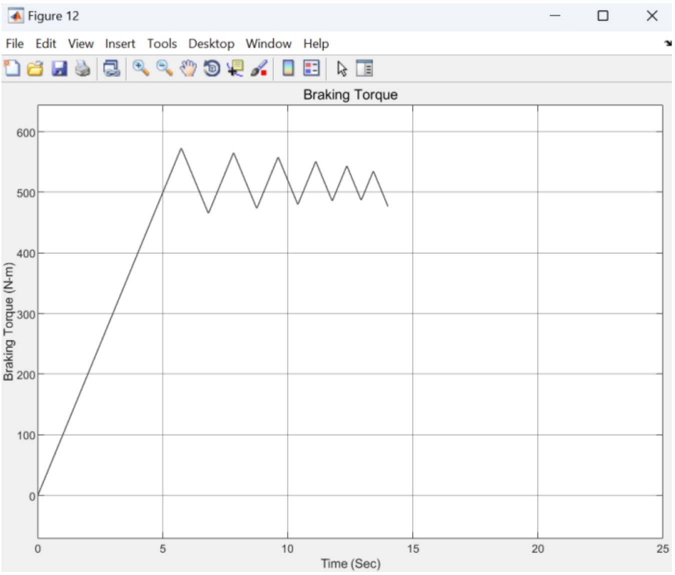


Chart -2: Braking Torque

Vehicle and wheel speed: Chart-1 shows the variation in car speed and wheel speed over time during the braking event. It highlights the effect of the ABS control system and the hydraulic brake in controlling the wheel speed and preventing wheel lock-up.

Braking Torque: Chart - 2 illustrates the variation in braking torque applied by the hydraulic brake system during the braking event. It shows how the torque generated due to braking adjusts to keep a constant slip ratio of 0.2, ensuring effective braking while preventing wheel lock.

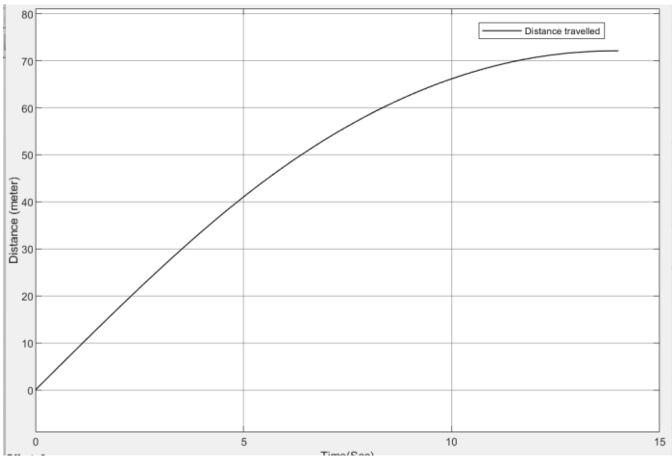


Chart -3: Stopping Distance of the car

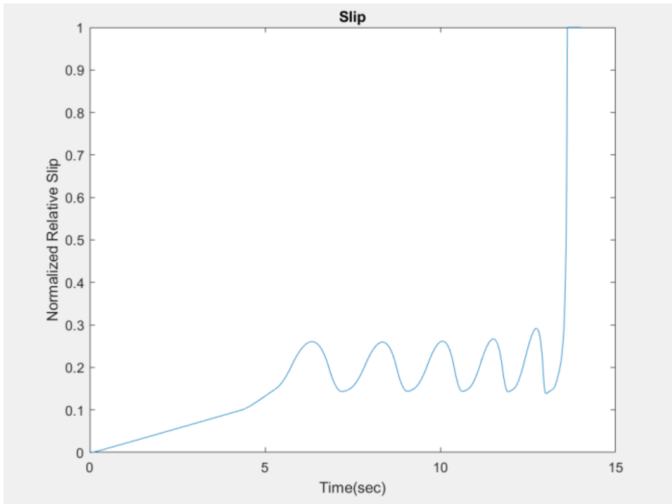


Chart -4: Slip ratio

Stopping Distance: Chart-3 illustrates the distance traveled by the car during the process of braking. It demonstrates the effectiveness of the hydraulic brake system and ABS in achieving the desired stopping distance while maintaining the constant slip ratio

Slip ratio: Chart-4 shows the variation in the relative slip of wheels overtime during the breaking event. It highlights the effect of bang bang controller on the slip ratio

3.2 MRB Model

A MATLAB model for simulating and analyzing the behavior of an MR Fluid Disc Brake has been developed. By developing the relationship between the current, magnetic field and braking torque. Mathematical analysis of the MR Fluid Disc Brake is performed. The total shear stress in the brake increases as the magnetic field intensifies, leading to the cessation of the rotating disc. To assess the behavior of the MR Fluid Disc Brake within a vehicle system, a Quarter Vehicle Model is utilized. The model considers various forces, including dynamic frictional force, rolling frictional force, and mass transfer during braking. Additionally, the integration of an Anti-lock Braking System (ABS) with MR Fluid brakes is achieved by designing a sliding mode controller that maintains a constant slip ratio of 0.2. This slip ratio corresponds to an appropriate current that has to be induced in the system for which the sliding mode controller has been utilized. The simulation is conducted using an initial vehicle velocity of 70 km/hr, and the resulting graphs of current, braking torque, wheel and vehicle speed, and slip ratio are generated.

Table -3: Parameters pertaining to MRB

Number of contact, N	4
Fluid gap (h)	0.1 cm
radius of the outer brake disc, r_z	0.168 m
radius of the inner brake disc, r_w	0.118 m
MR fluid viscosity, μ_p	0.09 Pa s
Electric constant, k	0.269 Pa m/A
Proportional gain, α	12.5 x $10^3 m^{-1}$
Basic coefficient, f_0	1 x 10^{-3}
Speed effect coefficient, f_s	5x 10^{-3}
Scaling coefficient, K_v	2.237

Working of MRB can be defined using the following mathematical analysis [7]

3.2.1 Mathematical modeling of MR Fluid Brakes

The behavior of MR fluid can be approximated by the Bingham plastic model:

$$\tau = \tau_H + \mu_p \dot{\gamma} \qquad (1)$$

Where τ_H is the yield stress developed due to the influence of magnetic field H , μ_p is the constant of plastic viscosity and $\dot{\gamma}$ is the shear rate

Braking torque can be calculated using:

$$T_H = \frac{2\pi}{3} N k \alpha (r_Z^3 - r_w^3) i = T_i i \qquad (2)$$

$$T_\mu = \frac{\pi}{2h} N \mu_p (r_Z^4 - r_w^4) \dot{\theta} = T_v \dot{\theta} \qquad (3)$$

$$T_b = T_H + Tv \qquad (4)$$

3.2.2 Vehicle modeling and sliding mode controller

Using Newton's law, the following equations can be derived:

$$m_t \ddot{x} = -\mu m_t g + \mu \frac{m_v h_{CE}}{l} \ddot{x} \qquad (5)$$

where $m_t = 0.25 m_v + m_w$

$$I\ddot{\theta} = -T_b + \mu R_w F_n - R_w F_r \qquad (6)$$

The equation (5) and (6) can be rewritten using equation (2) and (3) as:

$$\ddot{x} = \frac{-\mu g}{1 + \mu m_1} \qquad (7)$$

$$\ddot{\theta} = -I\tau_i - \tau_v \dot{\theta} + \mu \tau_n - \tau_r \qquad (8)$$

Where $\tau_i = T_i / I$, $\tau_v = T_v / I$, $\tau_r = R_w F_r / I$ and $m_1 = \frac{m_v h_{CE}}{m_t l}$

The control variable slip ratio can be defined as:

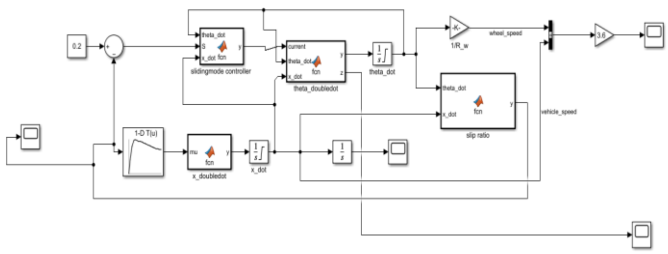
$$s_{rd} = \frac{\dot{x} - R_w \dot{\theta}}{\dot{x}} \qquad (9)$$

For the sliding mode controller, Slip ratio is chosen as the sliding surface. The control law comes out to be:

$$I = \frac{\hat{\mu} g \dot{\theta}}{(1 + \hat{\mu} \hat{m}_1) \dot{x} \tau_i} + \frac{1}{\tau_i} (\hat{\mu} \tau_n - \tau r - \tau_v \dot{\theta}) + \frac{\lambda \dot{\theta}}{\tau_i} + \frac{\dot{x} \lambda}{R_w \tau_i} (s_{rd} - 1)$$

$$+ \frac{1}{\tau_i} [(\eta + \frac{\mu^*}{\dot{x}} (g\dot{\theta} + \dot{x} \tau_n)) sgn(s)] \qquad (10)$$

The model can be built on simulink:



Preliminarily, chattering can easily be removed by creating a thin boundary layer of thickness ϕ and replacing $sgn(s)$ by $sat(s, \phi)$ [8]

$$sat(s(t), \phi) = \begin{cases} s(t)/\phi & |s(t)| < \phi \\ s(t) & otherwise \end{cases}$$

After implementing the saturated function following results can be obtained:

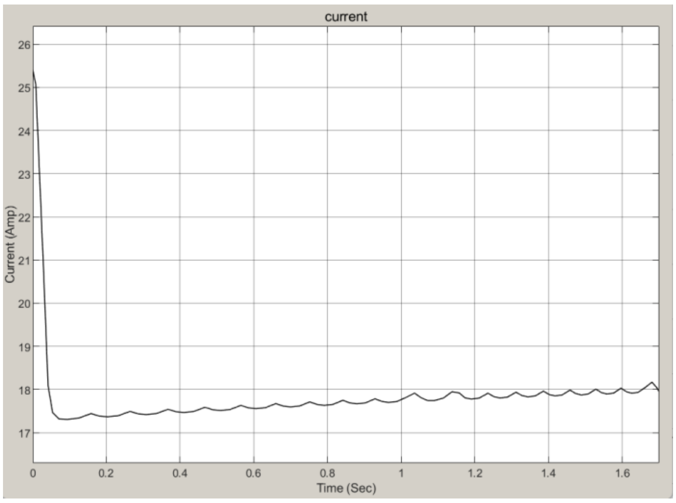


Chart -5 Current

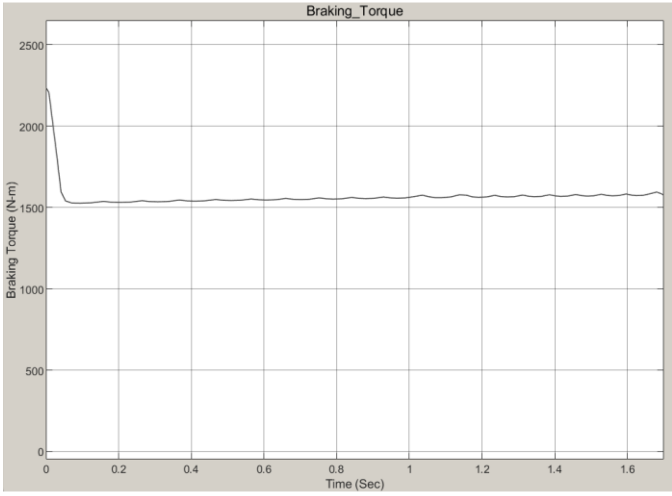


Chart -6 Braking Torque

As seen from Chart-5 and Chart-6, chattering still persists.

3.2.3 Chattering Reduction

Chattering is an undesirable phenomenon of oscillations of finite amplitude and frequency. Chattering is the primary obstacle in implementing sliding control. Chattering is an undesirable phenomenon because [9]:

- It leads to low control accuracy
- It causes high wear and tear of mechanical parts
- It causes Heat losses in electrical circuits

There are mainly two reasons for chattering:

1. It can be caused by fast dynamics, which are often neglected in an ideal model
2. The second reason, which is the reason for chattering in preliminary design. The reason is the use of a digital controller (since it has a finite sampling rate). It's known as discretization chatter

Here a modified saturated function can be created [10]:

$$msat(s(t),\phi) = \begin{cases} a(x,t)s(t)/\phi & |s(t)| < \phi \\ s(t) & otherwise \end{cases}$$

After implementing the modified saturated function following results can be obtained:

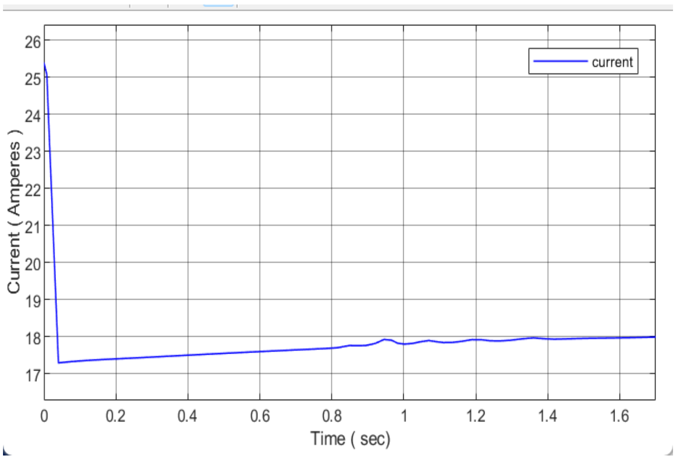


Chart -7 Current in Coil

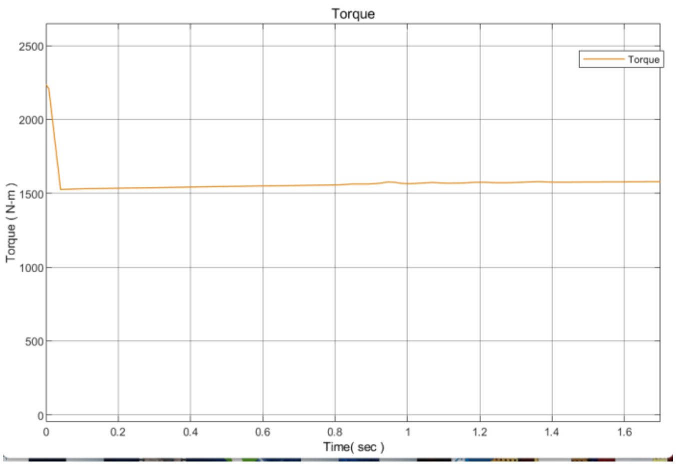


Chart -8 Braking Torque

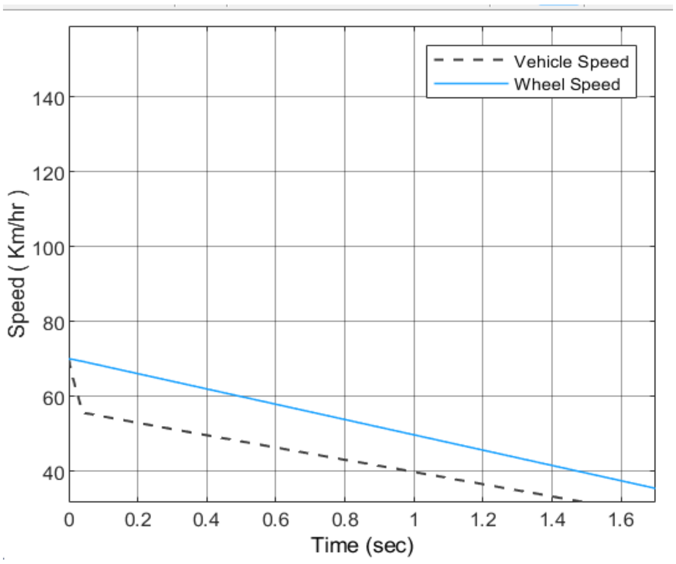


Chart -9 Vehicle and Wheel Speed

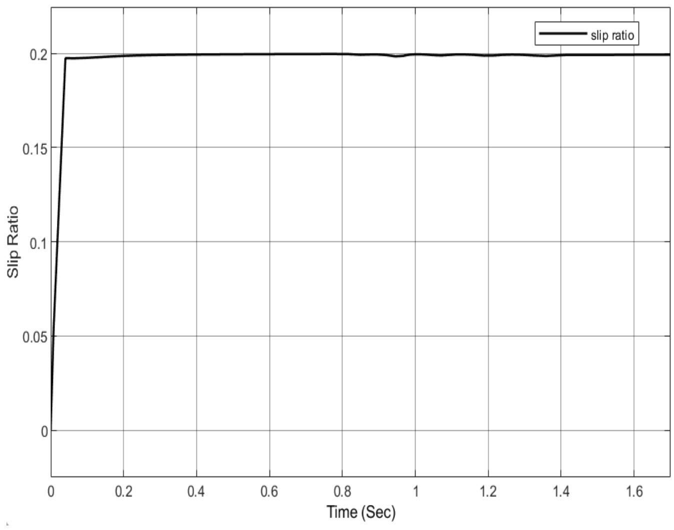


Chart -10 Braking Torque

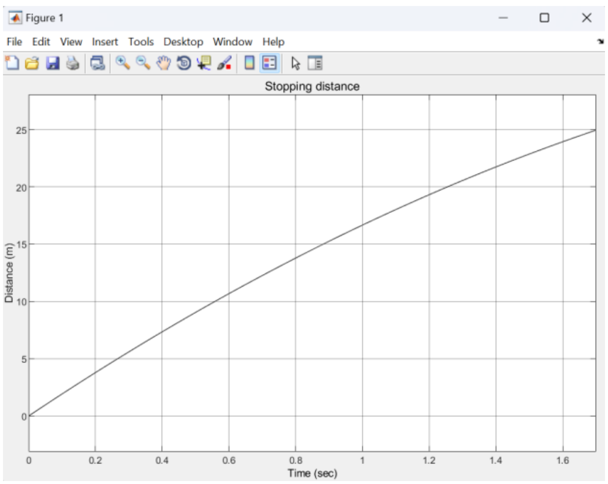


Chart -11 Stopping Distance

Current: Chart-7 shows the variation of current over time during the braking event. It highlights the control signal given by the sliding mode controller to keep a constant and optimal value of slip ratio.

Braking Torque: Chart-8 illustrates the relationship between the braking torque applied by the MR fluid brake and the resulting slip ratio. It demonstrates how the braking torque adjusts to keep a constant slip ratio of 0.2 throughout the braking process.

Vehicle and wheel speed: Chart-9 shows the variation in vehicle speed and wheel speed over time during the braking event. It highlights the impact of the ABS control system and the MR fluid brake in controlling the wheel speed and preventing wheel lock-up.

Slip ratio: Chart-10 shows the variation in relative slip of wheels over time during the braking event. It highlights the effect of sliding mode controller on the slip ratio

Stopping Distance: Chart-11 displays the distance traveled by the car during the process of braking. It demonstrates the effectiveness of the MR fluid brake and ABS system in achieving the desired

4. Comparative analysis between MRB and CHB

The graph in Chart-11 displays the distance traveled by the car

A comparative analysis between conventional hydraulic braking and MR (magneto-rheological) fluid brakes can be conducted by generating graphs of slip ratio as the control variable, as well as measuring stopping time, vehicle speed, and wheel behavior during braking. These graphs provide valuable insights into the performance and effectiveness of the respective braking systems. By examining the generated graphs, several conclusions can be drawn from the Table 4:

- MR Fluid braking system has much less stopping time due to continuous control of torque in contrast with discontinuous control in conventional hydraulic brakes
- As previously mentioned, the stopping time is significantly shorter in MRB which also translates to a much shorter stopping distance compared to CHBS (Conventional Hydraulic Braking System). This implies that the MRB system can bring the car to a complete halt in a shorter distance than the CBS system, indicating superior braking performance and efficiency.
- CBS system, indicating superior braking performance and efficiency. Since MRB uses a sliding mode controller it has significantly

shorter rising and settling time than CBS. Integral square error for MRB comes out to be 0.000475068 whereas for CHB it comes out to be 0.126. Hence MRB has better controller performance

Table -4: Comparison between MRB and CHB on various parameters

Comparative analysis	CHB	MRB	MRB (before chattering reduction)
Stopping distance	74 m	26 m	26 m
Stopping time	14 sec	2 sec	2 sec
Integral square error (ISE)	0.126	0.47×10^{-3}	0.57×10^{-2}
Integral Time-Weighted Absolute Error (ITAE)	6.746 8	0.311×10^{-5}	0.49×10^{-4}

5. Conclusion and Future Work

The MATLAB models of CHB and MRB were contrasted, which produced results revealing that MRB outperforms CHBS as the former can maintain an optimal slip ratio of 0.2 more effectively while the latter could not. The problem of chattering inherent in the SMC is solved by building a variable time-varying boundary layer around the switching surface. Graphs of current input, braking torque, stopping distance, vehicle speed, and wheel speed have been generated through the Simulink model.

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