VIRTUAL PROTOTYPING AND MATHEMATICAL MODELLING OF ABS ON TWO-WHEELER

MULTI-DISCIPLINARY DESIGN REPORT

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BONAFIDE CERTIFICATE

Certified that this project report titled **“Modelling of an ABS System”** is the bonafide work of **“Ashutosh Reddy (RA1611018010086), Mridav Goel (RA1611018010098), Satyam Dudhagara (RA1611018010102), Ashish Dubey (RA1611018010122), Pawan Raj Singh (RA1611018010146)”,** who carried out the project work under my supervision. Certified further, that to the best of my knowledge the work reported herein does not form any other project report or dissertation on the basis of which a degree or award was conferred on an earlier occasion on this or any other candidate.

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ABSTRACT

Safety and reliability of modern automobiles can be enhanced by Antilock braking system (ABS), traction control system etc. The traction control of the vehicle can be done fully or partially by the autonomous ABS system. The wheel slip is generally kept within a certain predefined range for an antilock braking system by using an on-off control strategy. In case of single wheel or bicycle model only constant normal loading on the wheels is considered, whereas. The vehicle braking system dynamics and its control for a two-wheel vehicle is illustrated here. The evaluation of performance of the ABS system under various operating conditions is done through modelling. Development of control law for this type of braking system is a simple task. A controller for ABS is developed to maintain the optimal slip value. It is found that with antilock braking, the vehicle's safety increases (in terms of stopping distance and maneuverability). The passenger comfort is improved when ABS controller is used for the mechanical braking part.

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Sincerely,
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1. INTRODUCTION

Mechatronics represents a 'systems design' approach in which mechanical, electronics and software systems are tightly integrated and are seen to influence each other, and therefore have a design impact on each other and the system as a whole. It is therefore essential that they all be designed as a true 'system'. In essence, a mechatronics design approach can be seen as an ideal form of concurrent engineering in which, different disciplines truly collaborate with (and influence) each other at all stages of the project. A Mechatronics approach can effectively be used when designing conventional consumer products. A technologically simple project involving a variety of technologies, including electronic, mechanical, and software systems is presented here for the ABS application. Through the tightly integrated use of mechatronics design principles, concurrent engineering and virtual prototyping allows for a fast-reiterative design approach and a short development cycle.

An Anti-Lock Braking System (ABS) is a safety anti-skid braking system used on aircraft and land vehicles, such as cars, motorcycles, trucks, and buses. ABS operates by preventing the wheels from locking up during braking, thereby maintaining tractive contact with the road surface.

Fig 1.1 ABS Symbol for vehicles

ABS is an automated system that uses the principles of threshold braking and cadence braking, techniques which were once practiced by skilful drivers before ABS were widespread. ABS operate at a much faster rate and more effectively than most drivers could manage. Although ABS generally offers improved vehicle control and decreases stopping distances on dry and some slippery surfaces, on loose gravel or snow-covered surfaces ABS may significantly increase braking distance, while still improving steering control. Since ABS was introduced in production vehicles, such systems have become increasingly sophisticated and effective. Modern versions may not only prevent wheel lock under braking, but may also alter the front-to-rear brake bias. This latter function, depending on its specific capabilities and implementation, is known variously as electronic brakeforce distribution, traction control system, emergency brake assist, or electronic stability control (ESC).

On a motorcycle, an anti-lock brake system prevents the wheels of a powered two wheeler from locking during braking situations. Based on information from wheel speed sensors the ABS unit adjusts the pressure of the brake fluid in order to keep traction during deceleration to avoid accidents. Motorcycle ABS helps the rider to maintain stability during braking and to decrease the stopping distance. It provides traction even on low friction surfaces. While older ABS models are derived from cars, recent ABS are the result of research, oriented on the specifics of motorcycles in case of size, weight and functionality. National and international organizations evaluate Motorcycle ABS as an important factor to increase safety and reduce motorcycle accident numbers.

Fig 1.2 ABS Brakes on a motorcycle front wheel

2. OBJECTIVES

The objectives for the case study are listed below:

1. Virtual Prototyping
    - Designing the CAD model for ABS system in SolidWorks software.
    - Importing the correctly mated assembly into Simscape Environment.
    - Designing simple control from Simscape to view simulation in the Mechanics Explorer of the MATLAB.
2. Model-in-loop simulation (Mathematical modelling)
    - Designing the control model by utilizing the system as a transfer function of the hydraulic system.
    - Relating the variables and implementing equations calculated for the model.
    - The Bang-Bang controller implementation.
    - Studying various transfer function modifications to observe and study results.
    - Plotting and studying the characteristics of the ABS model by comparing ABS On v/s ABS Off wheel speed, vehicle speed and slip values over time.

3. VIRTUAL PROTOTYPING

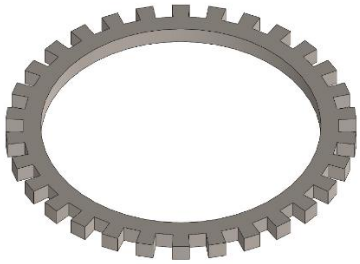
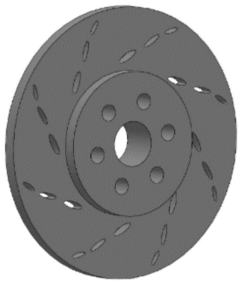
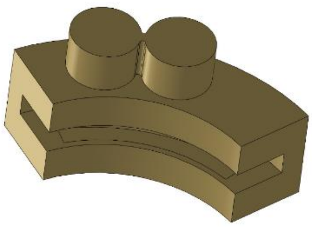
Virtual prototyping is a method in the process of product development. It involves using computer-aided design (CAD), computer-automated design (CAutoD) and computer-aided engineering (CAE) software to validate a design before committing to making a physical prototype. This is done by creating (usually 3D) computer generated geometrical shapes (parts) and either combining them into an "assembly" and testing different mechanical motions, fit and function. The assembly or individual parts could be opened in CAE software to simulate the behaviour of the product in the real world.

The product design and development process used to rely primarily on engineers' experience and judgment in producing an initial concept design. A physical prototype was then constructed and tested in order to evaluate its performance. Without any way to evaluate its performance in advance, the initial prototype was highly unlikely to meet expectations. Engineers usually had to re-design the initial concept multiple times to address weaknesses that were revealed in physical testing.

The Virtual Prototyping for the ABS system was made using SolidWorks and MATLAB Simscape for implementation of control and import the CAD model in the simulation environment.

The following table shows the representation of CAD part files and assembly compared with the actual parts and assembly.

Part/ Assembly	Actual Part	CAD Design
Hub and Spoke of the wheel		

Reluctor ring		
Brake Disc		
Brake Pads		
Brake Caliper		

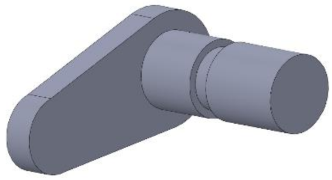
Speed sensor		
ABS Assembly		

Table 3.1 Tabular representation of CAD model and actual parts

Applications of the components used in an ABS are:

- Reluctor ring: A tone ring, also called a Reluctor ring, is a notched or toothed ring that's used in conjunction with a sensor to determine the number of revolutions or speed of revolutions. ABS rings fit on each wheel, working with sensors to send wheel-speed data to the Anti-lock Braking System controller. Using this data, the ABS controller stops the wheels from locking up by ensuring each one stays in sync. It does this by applying hydraulic pressure at just the right time.

- Wheel speed sensor: A wheel speed sensor or vehicle speed sensor (VSS) is a type of tachometer. It is a sender device used for reading the speed of a vehicle's wheel rotation. It usually consists of a toothed ring and pickup.
- Valves: There is a valve in the brake line of each brake controlled by the ABS. On some systems, the valve has three positions: In position one, the valve is open; pressure from the master cylinder is passed right through to the brake. In position two, the valve blocks the line, isolating that brake from the master cylinder. This prevents the pressure from rising further should the driver push the brake pedal harder. In position three, the valve releases some of the pressure from the brake.

- Pump: The pump in the ABS is used to restore the pressure to the hydraulic brakes after the valves have released it. A signal from the controller will release the valve at the detection of wheel slip. After a valve releases the pressure supplied from the user, the pump is used to restore a desired amount of pressure to the braking system. The controller will modulate the pump's status in order to provide the desired amount of pressure and reduce slipping.
- Controller: The controller is an ECU type unit in the car which receives information from each individual wheel speed sensor. If a wheel loses traction, the signal is sent to the controller. The controller will then limit the brake force (EBD) and activate the ABS modulator which actuates the braking valves on and off.

The CAD Model is imported to the MATLAB Simscape environment by using and add-on feature for both the software. Proper and correct mate definitions in Solidworks would result in correct Simscape Multibody design of the model with correct joints in the model and their configuration. The figure below shows the imported CAD model in a Simscape Environment and its Mechanics Explorer for CAD model Simulation.

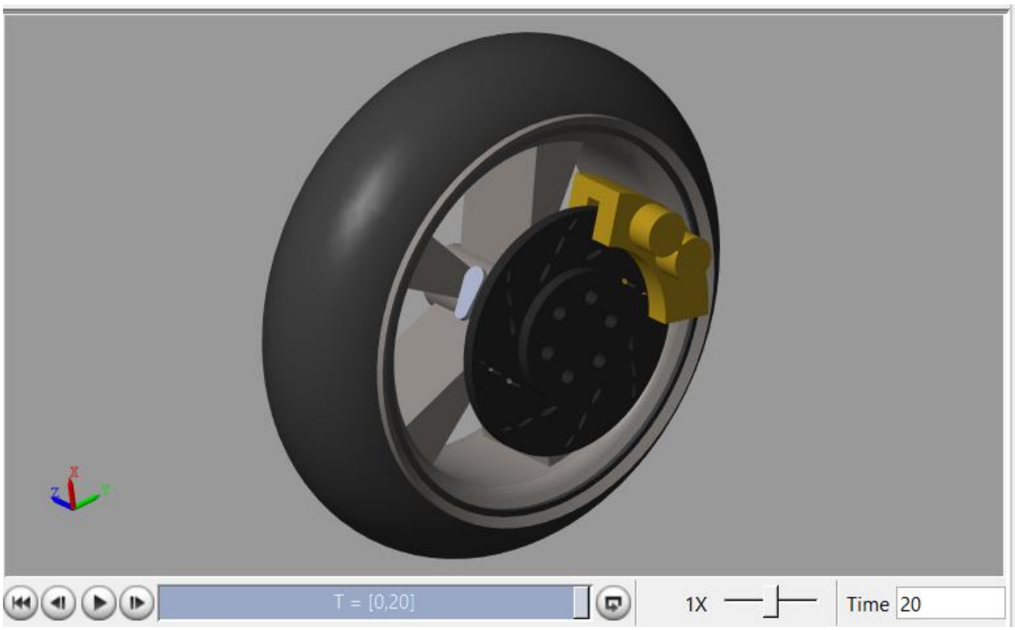


Fig 3.1 Mechanics explorer in MATLAB

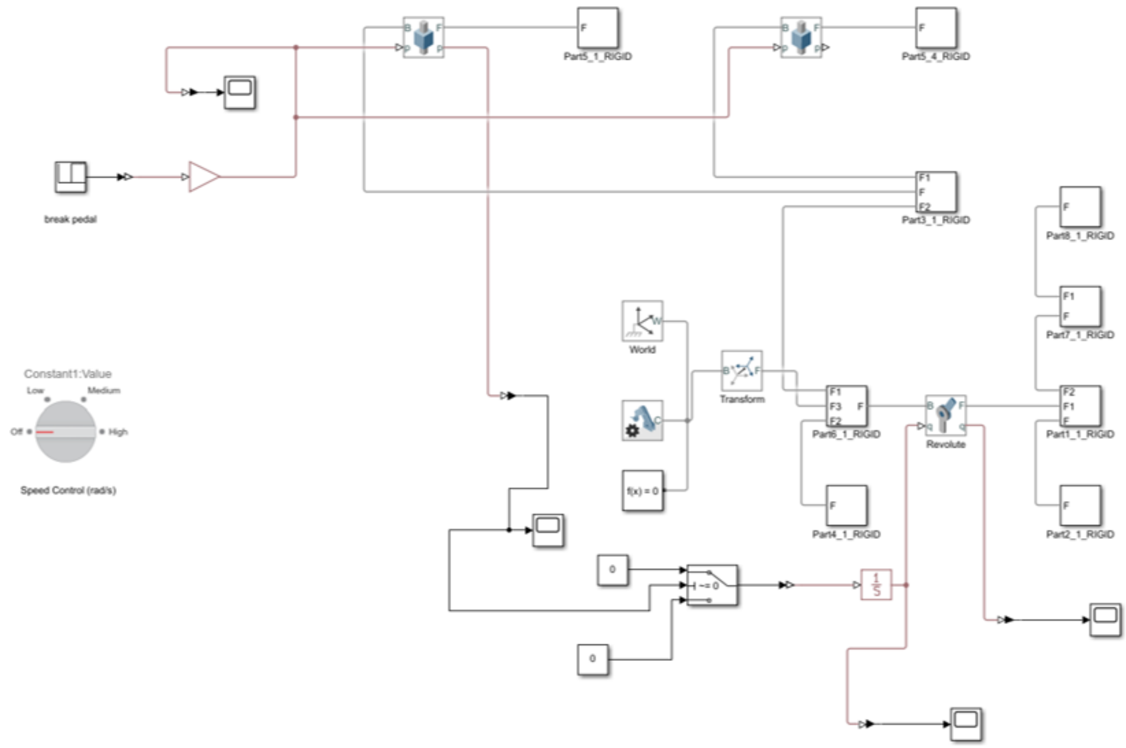


Fig 3.2 Simscape model of the CAD Design with simple speed control and braking

4. MATHEMATICAL MODELLING

Model-in-the-loop testing (MIL) and simulation is a technique used to abstract the behaviour of a system or sub-system in a way that this model can be used to test, simulate and verify that model. By using an industry standard toolchain such as Simulink for model definition you can test and refine that model within a desktop environment, allowing a complex system to be managed efficiently. Once you have modelled your control system or environment (plant model), you can use this powerful offline simulation environment to test your controller strategies.

Mathematical modelling and simulation bring significant benefits in terms of understanding the braking phenomena and the impact of different parameters on the braking performance of a vehicle. Anti-lock braking systems (ABS) are meant to control the wheel slip in order to maintain the friction coefficient close to the optimal value. Wheel slip is defined as the relative motion between a wheel (tire) and the surface of the road, during vehicle movement. Wheel slip occurs when the angular speed of the wheel (tire) is greater or less compared to its free-rolling speed.

In order to simulate the braking dynamics of a vehicle, we are going to implement simplified mathematical models (bike model) for both vehicle and wheel. Also, a simplified ABS controller is going to be implemented in order to emulate the braking torque in slip conditions.

Equations of velocity and slip:

$$W_v = V_{V/}R$$

Slip, $s = 1-W_w/W_v$ = 1- (wheel angular speed)/(velocity angular speed)

Where,

W_v = vehicle linear speed / wheel radius

V_v = vehicle linear speed

R_r = wheel radius

W_w = wheel angular speed

Now,

We need to find W_v and W_w to find slip where V_v & R_r will be given.

Friction force on wheel

$$F_f = umg/2 \text{ (two-wheeler where m = total mass)}$$

$$U = \text{coefficient of friction}$$

Note that u varies for different slip values.

Deceleration due to friction, $a = F_f /m = ug/2$

$$\text{Vehicle speed} = \int (-ug/2)\, dt = V_v$$

{negative sign indicates deceleration so that the speed will be educing with time}

$$Vv*1/R_r = W_v \text{ \{vehicle angular speed\}}$$

Also, stopping distance can be found by differentiating vehicle linear speed

$$d(V_v)/dt = S_d$$

Now, to find the W_w i.e., wheel angular velocity we use tyre torque,

$$T_t = F_f \text{ x } R_r$$

This tyre torque will be subtracted from brake torque to obtain net torque,

Therefore, Net torque = brake torque - tyre torque

$$T_N = T_B - T_T$$

Now, to find angular acceleration of wheels,

$$\alpha_w = T_N/I \quad \{ \text{As, } T_w = I.\alpha \}$$

Therefore, wheel angular speed = $W_w = \int d_w\, dt$

$$\text{i.e., } \int d_w\, dt = W_w$$

Thus, relative slip can be obtained as,

$$\text{Slip(S)} = 1 - W_w/W_v$$

This 'S' value can be fed back to find 'μ' values at a given instant as well as for the 'bang-bang' controller.

Bang-bang controller is just a $sig_n(x)$ function give as,

$$\text{i.e., } y = sig_n(x) = \{1, x > 0; 0, x = 0; -1, x < 0$$

Thus, the difference between the desired and actual slip i.e., 'error in slip' is fed to the bang-bang controller.

Thus, this (1, 0, -1) is sent to the hydraulic first order model which produces brake pressure output which when multiplied to the factor 'K_f' (multiplication of piston area and when radius) to obtain braking torque.

Based on the above mathematical equation a Simscape model is made for the application and the plant model is considered as a transfer function for the hydraulic lag. This transfer function has order of one with numerator value describing the gain while the constant in the denominator is the time constant.

The specifications of the model is given below in the table:

Variable/ Parameter	**Description**	**Value used**
Ctrl	ON/OFF Abs	1/0 for on/off ABS
g	Gravitational Acceleration	9.8 m/s^2
I	Inertia	1.572 kg m^2 =37.32 lb ft^2
Kf	Pressure to torque	0.00566 m^3 = 0.2 ft^3
M	Mass of Vehicle	160 kg
BPmax	Max. Brake Torque	2000 lb ft
Rr	Radius of wheel	305 mm = 1 ft
Tb	Time constant of Hydraulic	0.01
V0	Initial Velocity	User defined (in m/s^2)
Slip	Slip values	Array (1x21)
Ds	Desired slip	0.2
Mu	Coefficient of friction	Array (1x21)

Table 4.1 Model Parameters and Inputs

The Simscape model for the above mathematical model described in theory is given below as:

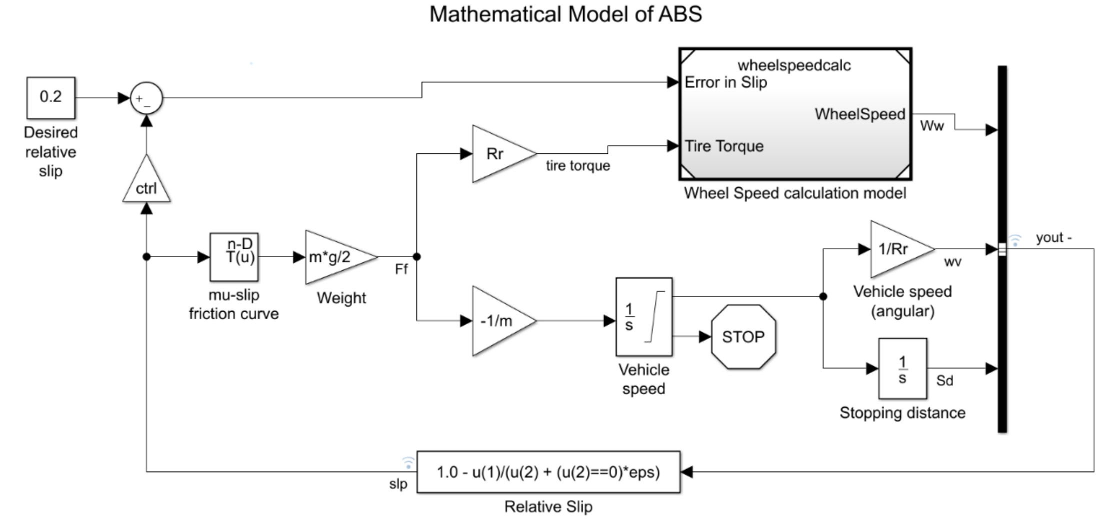


Fig 4.1 Mathematical model

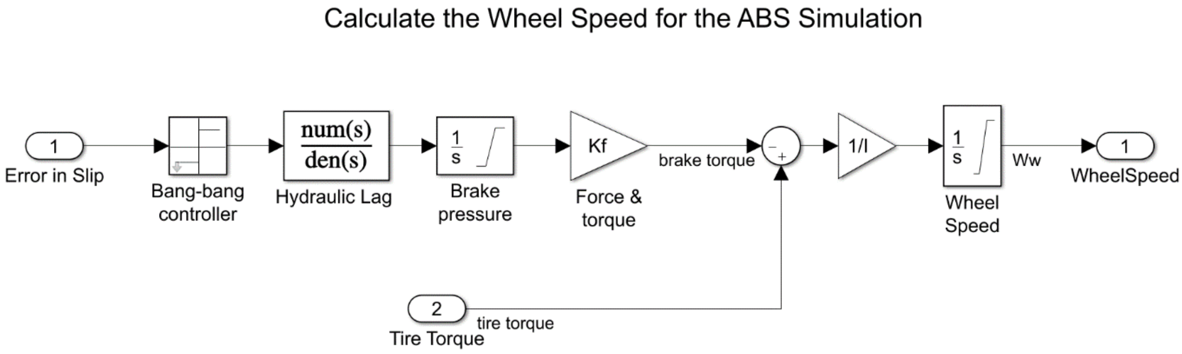


Fig 4.2 Calculate Wheel Speed Model

To control the rate of change of brake pressure, the model subtracts actual slip from the desired slip and feeds this signal into a bang-bang control (+1 or -1, depending on the sign). This on/off rate passes through a first-order lag that represents the delay associated with the hydraulic lines of the brake system. The model then integrates the filtered rate to yield the actual brake pressure. The resulting signal, multiplied by the piston area and radius with respect to the wheel (Kf), is the brake torque applied to the wheel.

The model multiplies the frictional force on the wheel by the wheel radius (Rr) to give the accelerating torque of the road surface on the wheel. The brake torque is subtracted to give the net torque on the wheel. Dividing the net torque by the wheel rotational inertia, I, yields the wheel acceleration, which is then integrated to provide wheel velocity. In order to keep the wheel speed and vehicle speed positive, limited integrators are used in this model.

5. RESULTS

The simulation scenario is braking from an initial speed of v_0 [mps] until a complete vehicle stops, with the driver braking heavily.

There are two test cases:

- **without ABS**: the slip controller is disabled by setting the parameters **CTRL = 0**
- **with ABS**: the slip controller is enabled by setting the parameters **CTRL = 1**

The Simscape simulation will is run for **15** s.

The results are obtained as follows for both ABS ON and OFF:

Fig 5.1 Wheel velocity and Vehicle velocity with time (ABS ON)

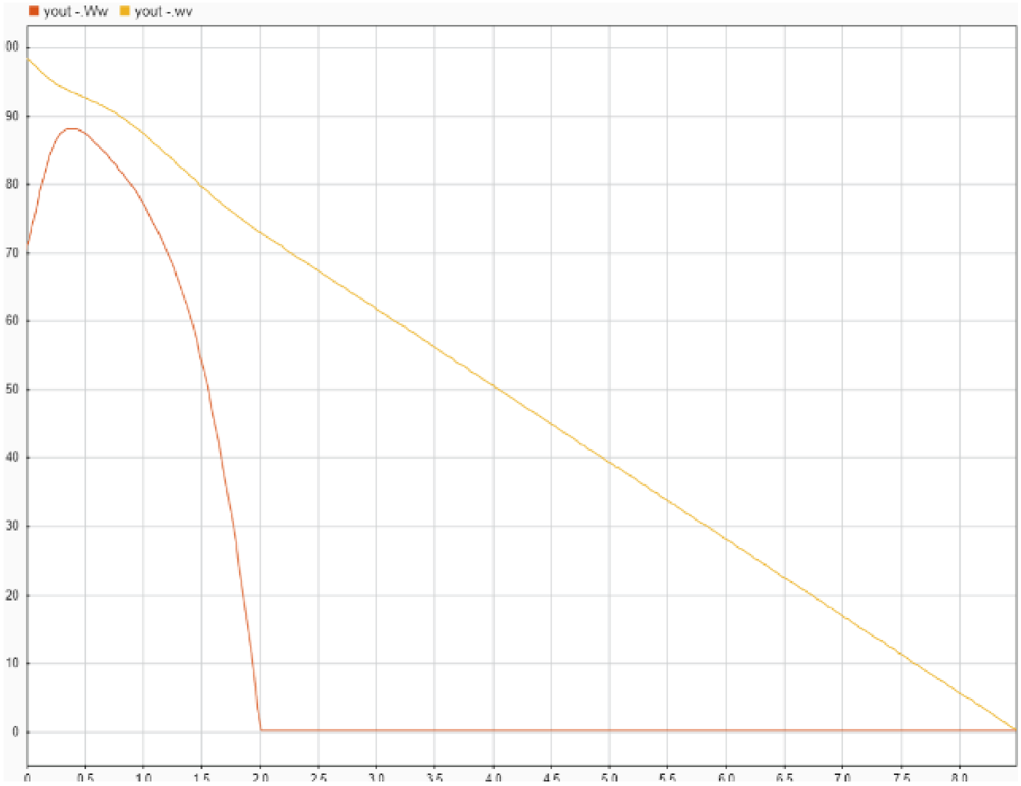


Fig 5.2 Wheel velocity and Vehicle velocity with time (ABS OFF)

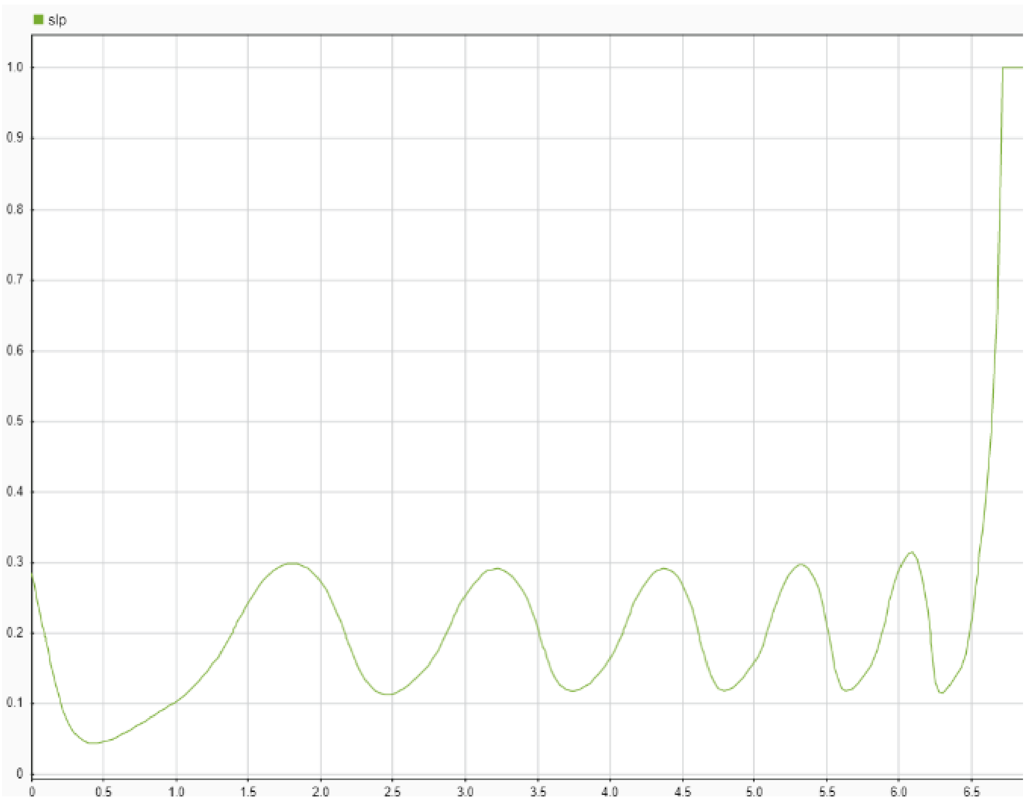


Fig 5.3 Slip with time (ABS ON)

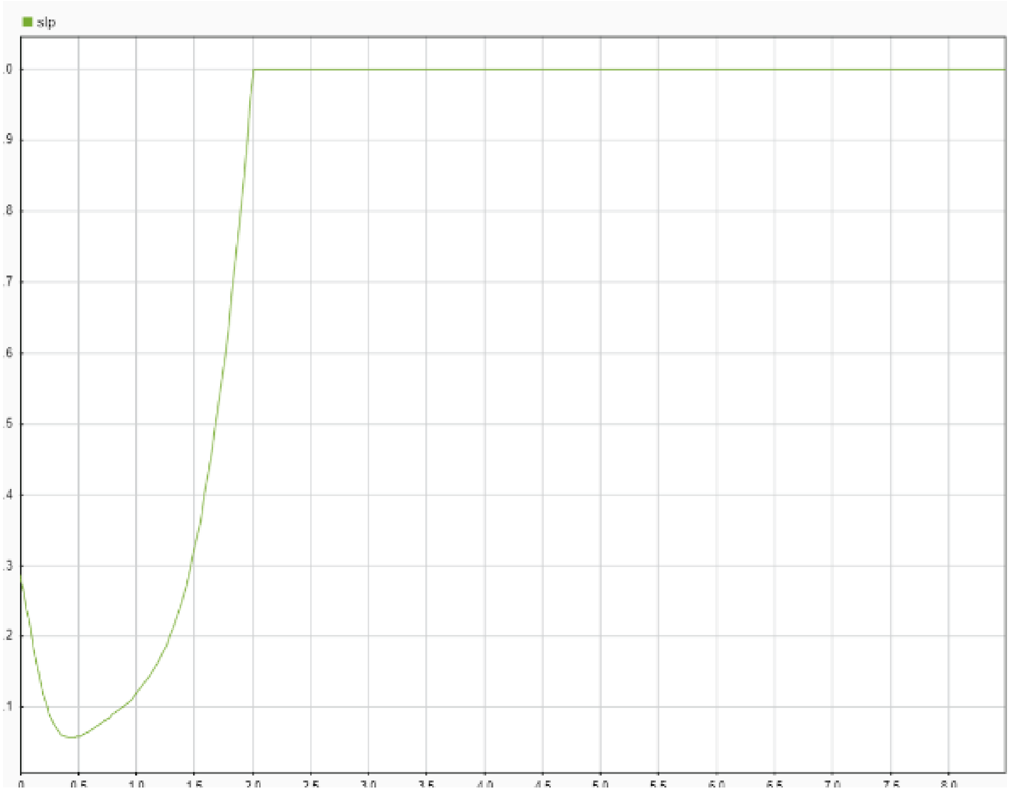


Fig 5.4 Slip with time (ABS OFF)

6. CONCLUSION AND FUTURE SCOPE

This model shows how you can use Simulink to simulate a braking system under the action of an ABS controller. The controller in this example is idealized, but you can use any proposed control algorithm in its place to evaluate the system's performance. You can also use the Simulink Coder with Simulink as a valuable tool for rapid prototyping of the proposed algorithm. C code is generated and compiled for the controller hardware to test the concept in a vehicle. This significantly reduces the time needed to prove new ideas by enabling actual testing early in the development cycle.

For a hardware-in-the-loop braking system simulation, you can remove the 'bang-bang' controller and run the equations of motion on real-time hardware to emulate the wheel and vehicle dynamics. You can do this by generating real-time C code for this model using the Simulink Coder. You can then test an actual ABS controller by interfacing it to the real-time hardware, which runs the generated code. In this scenario, the real-time model would send the wheel speed to the controller, and the controller would send brake action to the model.

The model is tested only for the dry concrete surface as the given slip v/s mu graph holds the description of a dry surface of concrete and rubber wheel on it. This can be extended for various surfaces in the model such as wet concrete, snow and even ice. Also simulating the whole surface in the CAD simulation with vehicle movement as well as steerability control for various roads could be simulated as a future scope for this application.

7. REFERENCES

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- https://en.wikipedia.org/wiki/Anti-lock_braking_system
- https://www.youtube.com/watch?v=ZQK3A3vik8o

APPENDIX

MATLAB code for parameter definition:

```
ctrl = 1; % ABS on/off

g = 9.8/0.3048; % Acceleration due to gravity

I = 37.32; % Inertia of wheel (from Solidworks model)

Kf = 0.2; % pressure to force to torque conversion factor

m = 160*0.157473; % vehicle weight

BPmax = 2000; % Max. brake pressure

Rr = 0.305/0.3048; % wheel radius

TB = 0.01; % Braking time constant

v0 = 30/0.3048; % Initial velocity

eps = 2.2204e-35;

slip = [0, 0.0500, 0.1000, 0.1500, 0.20000, 0.2500, 0.3000,
0.3500, 0.4000, 0.4500, 0.5000, 0.5500, 0.6000, 0.6500,
0.7000, 0.7500, 0.8000, 0.8500, 0.9000, 0.9500, 1];

mu = [0, 0.4000, 0.8000, 0.97000, 1, 0.9800, 0.9600, 0.9400,
0.9200, 0.9000, 0.8800, 0.8550, 0.8300, 0.8100, 0.7900,
0.7700, 0.7500, 0.7300, 0.7200, 0.7100, 0.7000];
```