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Modeling and Simulation of Off-Road Vehicle Mobility with Driving Torque Distribution Control on Split Adhesion Conditions

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ABSTRACT:

This paper presents a theoretical model for simulation of driving torque distribution control to improve off-road vehicle mobility on split adhesion conditions. The model is constructed and then validated with experimental test rig results. A MATLAB simulink modeling of an electronically controlled device is used to modulate the applied force over multi-plate clutches located between the automotive driven axle shafts and the stationary hub. On driving over split adhesion roads, the control device brakes the spinning axle wheel running over ground low adhesion side and accordingly biases more torque to the other wheel with good adhesion side. This would improve the vehicle off-road mobility and save the power losses on low adhesion wheels. The proposed control model had been validated with experimental results obtained from an experimental tests conducted on a specially designed and built test rig. Consequently, the proposed control system has been embedded within a full car theoretical model to predict the vehicle performance on split adhesion drive conditions. The results showed that the constructed simulink model is suitable for simulating the proposed controlled device for torque distribution after matching the simulation results with experimental test rig results. Moreover, the proposed control model could be implemented to improve the transmitted traction power to the road from a conventional deferential.

KEYWORDS:

Off-road vehicle; Automotive torque distribution; Driving torque distribution control; MATLAB simulink

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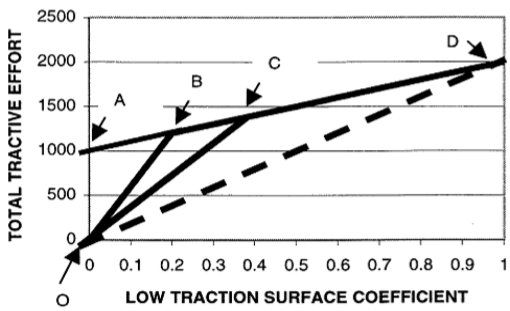
1. Introduction

Improving the vehicle traction control is one aim of recent research. One aspect of this aim is the controlling of torque distribution between the driving wheels. Consequently, active clutches and actively controlled slip clutches are the preferred choices for the mid-range to entry-performed vehicles. Moreover, permanent All Wheel Drive (AWD) is preferred for off-road vehicles as well as high performance vehicles. Torque vectoring devices can in contrast to Limited Slip Differential (LSD), actively transfer the torque to any output shaft regardless of current speed on any of the output shafts. These systems are able to control each wheel's torque accurately and individually in any given situation. From developing a new differential design, with hope to definitely eliminate the disadvantages of the LSD, there was guidance in design concept [1]. On the other hand, analytical evaluation of the performance of the Torsen differential, through mathematical modeling, led to a predicted performance in good correlation with experimentally measured data [2]. Fig. 1 shows the relative improvement from a differential with torque bias illustrated in two cases; first is moving in straight and equal road adhesion and second is moving on different road adhesions (brake applied to the right side) [2].



OBD = 5.0:1 bias ratio, OCD = 2.5:1 bias ratio
OD = the open differential line & AD = the locked differential line

Fig. 1: Traction gain of vehicle equipped with torque bias ratio [2]

Further research discussed both torque and speed sensing LSDs to evaluate the performance of speed sensing LSDs on engine and brake Traction Control Systems (TCS) [3]. Moreover, the benefits of adjustable tuning in handling, mobility, and compatibility with other vehicle systems, such as Antilock Braking System (ABS), TCS, and Stability Control as Electronic Stability Program (ESP) are studied to optimize the performance of vehicles equipped with electronically controlled differential [4]. Simulation of a typical sport sedan with fully independent control of torque distribution has been used to determine which torque distribution parameters have the greatest impact on the vehicle course and acceleration [5]. The influences of controlled Torque Management Devices (TMDs) on vehicle dynamics for various driveline layouts had been clarified [6]. Various driveline concepts had been explained using electronically controlled TMD ranging from on-demand (hang-on coupling) to full time AWD systems with a center differential [6]. On the other hand, modeling of torque biasing device of a Four Wheel Drive (4WD) system has been introduced for improving the vehicle stability and handling, where the effectiveness of the torque biasing system in achieving yaw stability control is presented [7].

Liu et al [8] discussed the driveline systems with electronically controllable torque biasing devices for vehicles yaw stability applications introduced by Bond Graphs. Mashadi et al [9] investigated the improvement of vehicle dynamic performance using a rear electronically controlled LSD. The control strategy is based on vehicle yaw rate, rear wheel slip values, and braking subsystem on the front wheels with optimal Linear Quadratic Regulator (LQR) controller on an elaborated six degrees of freedom linear vehicle model. Active differential dynamics using Bond Graph modeling technique was also presented in [10]. A lumped-parameter dynamic model of an electromechanically actuated wet clutch found in active LSD had also been presented in [11]. Torque Vectoring Differential (TVD) system based on vehicle stability control was proposed to achieve additional torque steering for improving vehicle steer-ability and stability. Firstly, 4WD vehicle model is set up and then the virtual controllers based on fuzzy logic control including the yaw moment controller and TVD model are designed using MATLAB SIMULINK [12].

2. Open differential vs. LSD

The various mathematical models of differentials are illustrated and SIMULINK model to multi-plate controllable clutch has been built to validate the result obtained experimentally from the developed test rig. Open differential as shown in Fig. 2(a) and LSD as shown in Fig. 2(b) are used in this study.

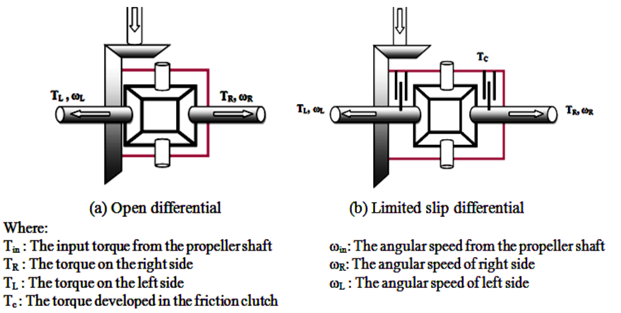


Fig. 2: Torque and speed distribution of open differential and LSD

In an open differential, the input torque from the propeller shaft is distributed in semi-equal percent to left and right shafts, while the input shaft speed is distributed between each shaft according to individual wheel-road adhesion conditions. The maximum torque which is transmitted through the differential is the minimum torque generated on slippery side. The open differential will not be able to produce more torque than that on the wheel with the least grip. This means that if one wheel on low adhesion and the result is that the vehicle cannot move off. Therefore LSD will, by various means, transfer torque from the wheel with less grip to the wheel with more grip. Then LSD tries to eliminate the speed difference between the two output shafts [2].

3. Experimental test rig

A test rig of a rear axle of AWD car as shown in Fig. 3 has been designed and built at the Automotive Engg. Dept., Faculty of Engg. - Mataria, Helwan University, Egypt. Fig. 4 illustrates the test rig measurements system and controlling system. The adhesion between the road and tire was simulated by braking of rear driving axle with a hand brake control on each side step by step to apply a different adhesion on each side. A synchronized (3 phases, 20 HP, 1475 rpm) AC motor was used as input source to the driving axle. A brake loading system is used to simulate the road resistances on the left and right sides of the drive axle. Sensors have been used for measurement of torque and speed of both the left and right half-shaft. Wheel speed is measured by two photoelectric tachometers. The torque produced on both driven axle sides are measured using strain-gauges. For a detailed description of the test rig and the actual results can be found in [13-14]. LABVIEW program with data acquisition system has been equipped to pick up the physical values from the sensors and analyze the reading to control the actuators with desired values according to the process flow chart shown in Fig. 5.

Fig. 3: Test rig of a rear axle of all wheel drive

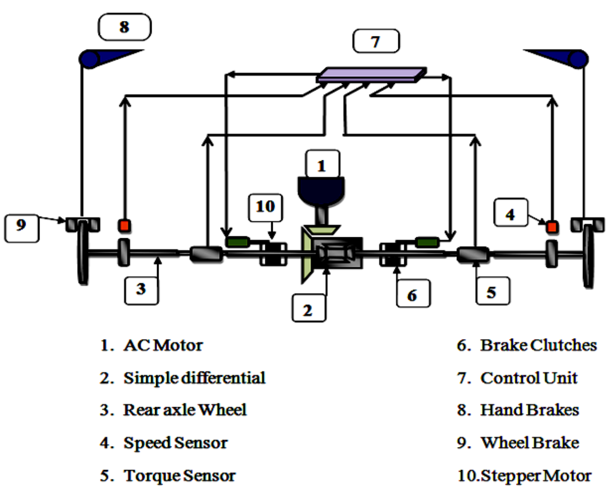


Fig. 4: Torque distribution measurement and control systems

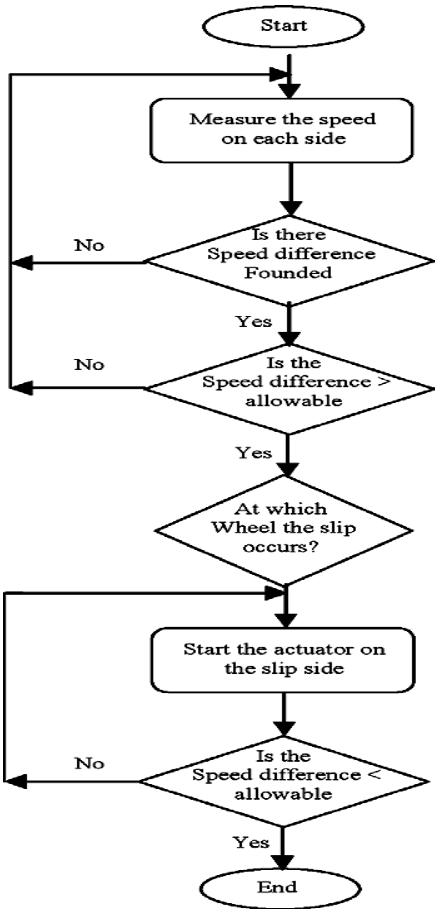


Fig. 5: Process flow chart of clutch control

4. Test rig models

4.1. Passive test rig model

Fig. 6 shows the test rig model consisting power source, differential and road resistance SIMULINK models. Each sub-model is built to simulate the real test rig with the same conditions to validate the results with the test lab results. Sensors and display systems are collected in measuring system sub-model. A three phase AC motor was simulated by the output power, motion and input volt. In the model the input parameters are 155 W and 1450 rpm. The model has one output port which can be connected to the differential instead the vehicle motor. The motor output torque and speed are measured by rotation and torque sensors to obtain right test data. The differential icon is used to simulate the torque and speed of input and output driven shafts. B is the input port and F_1, F_2 are the output ports. The differential gear ratio is inserted in the driver model that runs the overall assembly model. The speed and torque generated from differential can be measured by the two block sensors where the torque is inserted in series with the drive line. The motion is connected with the drive line in parallel and the reading is displayed on the scope. The road resistance can be simulated as controllable friction brake. The exerted brake force will be applied on port (P). The port (B) is the shaft to be braked and (F) is the stationary port. The road resistance model shown in Fig. 7 has friction brakes for the left and right sides.

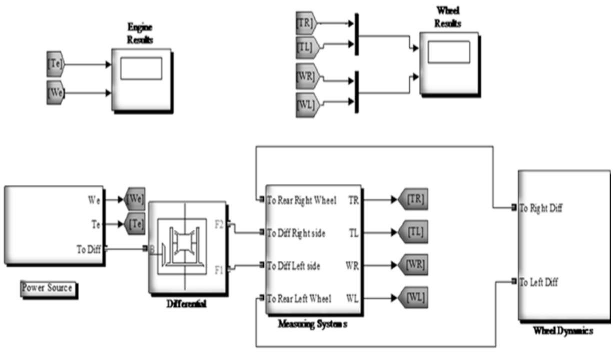


Fig. 6: Test rig SIMULINK model with open differential

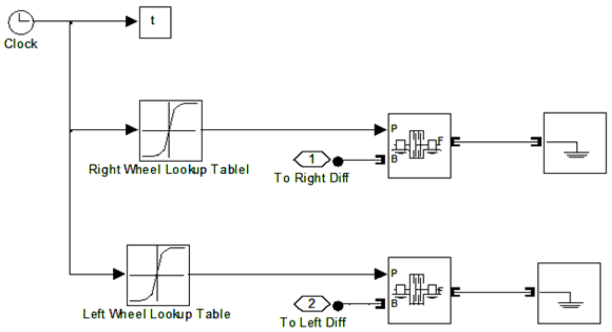


Fig. 7: Road resistance SIMULINK model

A lockup table block was used to apply the brake force by the required steps. The data used in the lockup table and all given data is programmed in the MATLAB (.m file) to drive the whole model. The measuring system sub-model is a collection of torque and motion sensors to measure the torque and speed on the right and left shafts. The shaft inertia and display system are inserted in this sub-model to simulate the real system. The data output is converted to SI units by using the gain block inserted between the output data and display system. To run the open differential test rig, a MATLAB program containing each data such as differential gear ratio, lockup table and operating time which is needed to play the SIMULINK model is written.

4.2. Active test rig model

Fig. 8 shows the controllable clutch model that contains two friction clutches controlled by a programmed switch by with if-else loop system to actuate the clutches when the speed difference has increased more than that expected when the vehicle negotiates its minimum turning radius.

4.3. Full car model with controllable differential

A full car SIMULINK model with controllable clutch is used to evaluate the effect of using a clutch with open differential on vehicle performance when moving on split road adhesion. Fig. 9 shows a full car rear wheel drive with diesel engine 150 kW at 5000 rpm as a prime mover model. The gear box ratio assumed to be direct drive (i.e. 1:1). The main parameters are: open differential with 3.6 gear ratios, vehicle mass 1600 kg, CG distance from to rear axle 1.6 m, CG distance to front axle 1.4m and height 0.5 m, frontal area 3m^2, drag coefficient 0.4 and tire rolling radius 0.3 m. The wheel dynamics sub-model shown in Fig. 10 simulates the front and rear axles and all the vehicle dynamics.

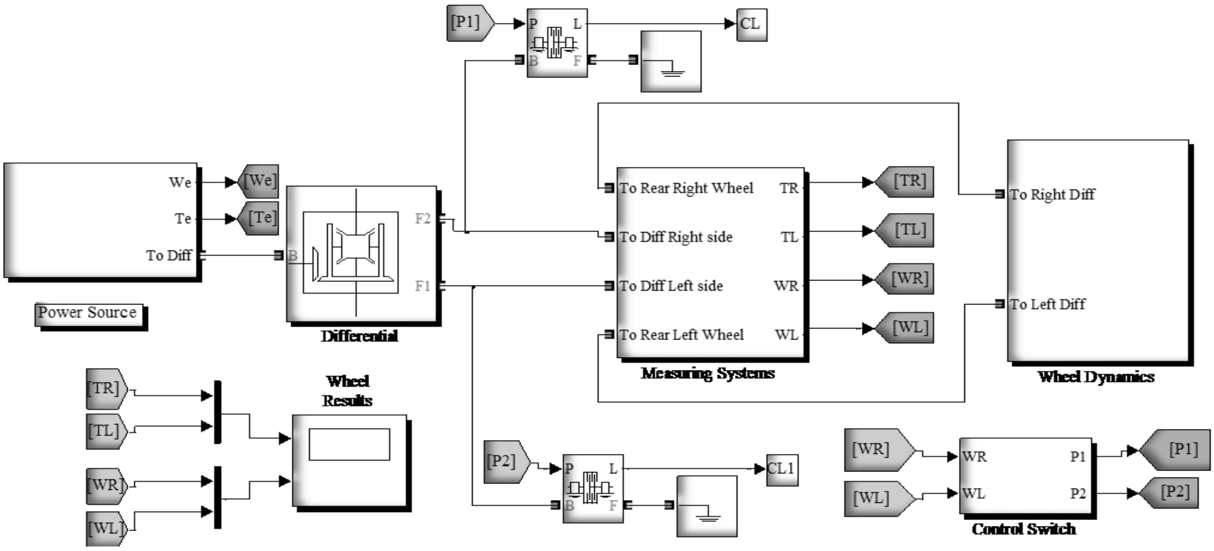


Fig. 8: Test rig model with active controllable clutch model

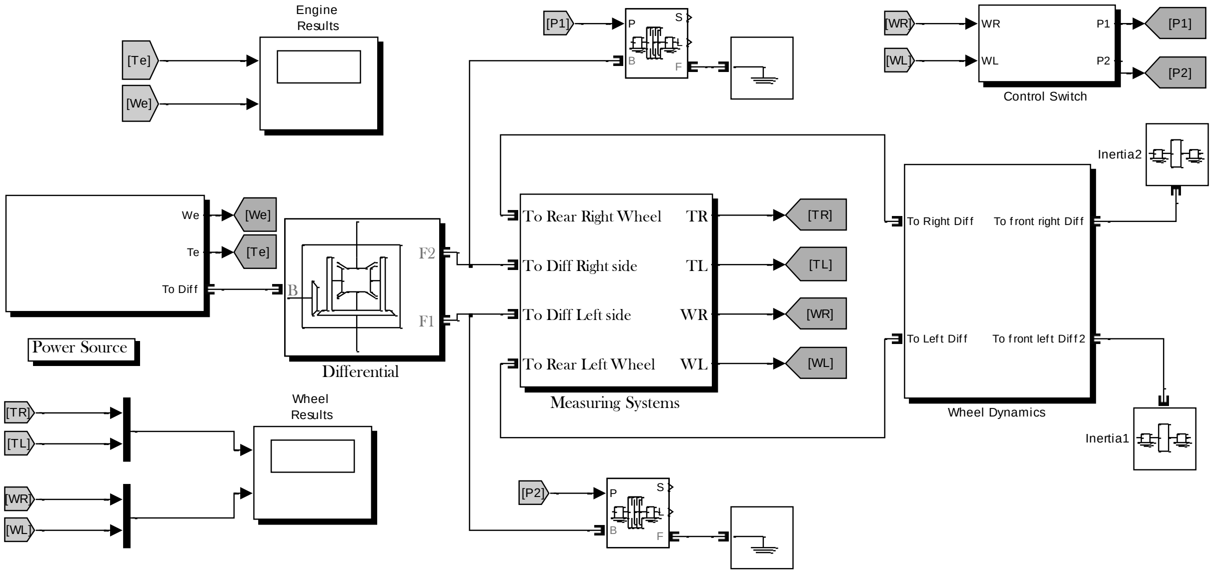


Fig. 9: Full car model with controllable clutch mechanism

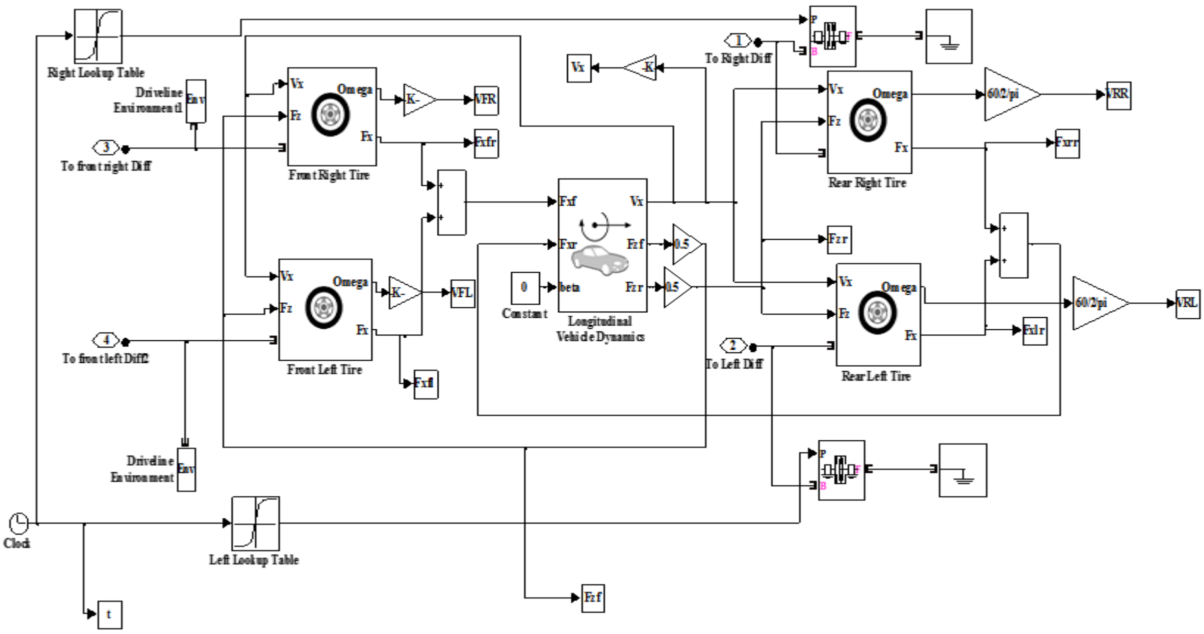


Fig. 10: Wheel dynamics sub-model simulating the front and rear axles and all vehicle dynamics

5. Results and discussions

The test rig was simulated using MATLAB SIMULINK software to validate the result obtained from the lab tests to ensure that the model gives appropriate lab results and accordingly a full car simulation model can be built.

5.1. Theoretical results of passive open differential

Figs. 11 and 12 show the results of measured torque, rotational speed and axle power for first step and second step at left and right half-axles respectively for simulink model comparison with test rig results without modulating the multi-plate clutches when moving on split surfaces. All model results are partially identical to the test results especially with respect to speeds. SIMULINK model torque results slightly differ from the obtained experimental results. The reason is that the model is based on torque equality at both sides but actually there was an unequal friction resistance on both axle sides. The power results in SIMULINK model differ from the experimental results as the power is the result from the product of torque and rotation speed.

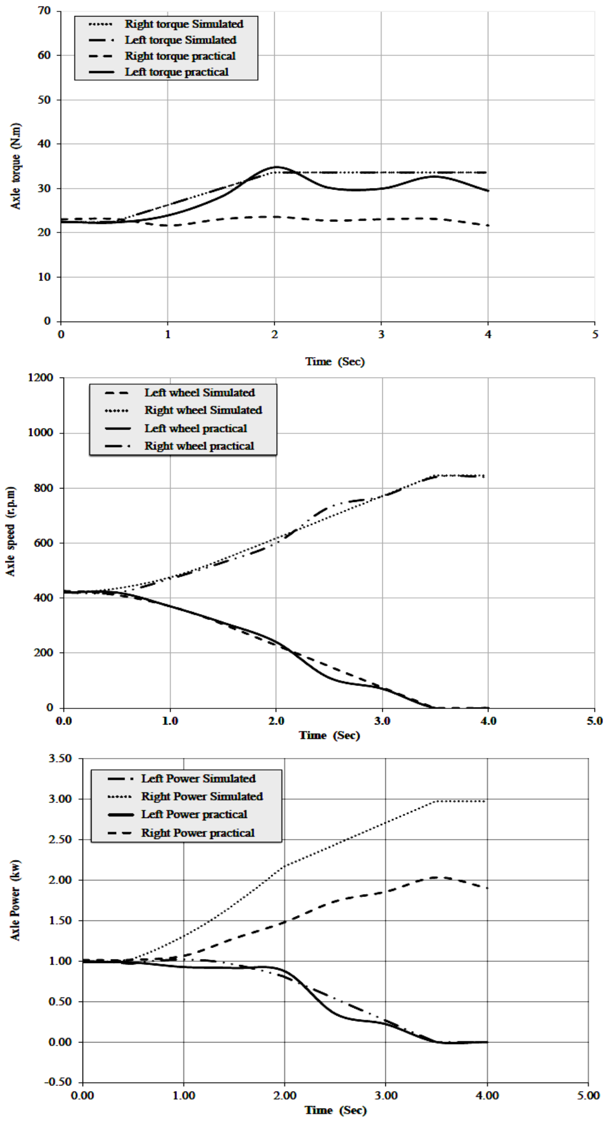


Fig. 11: Axle speed, torque and power without activating controllable device for 1st step

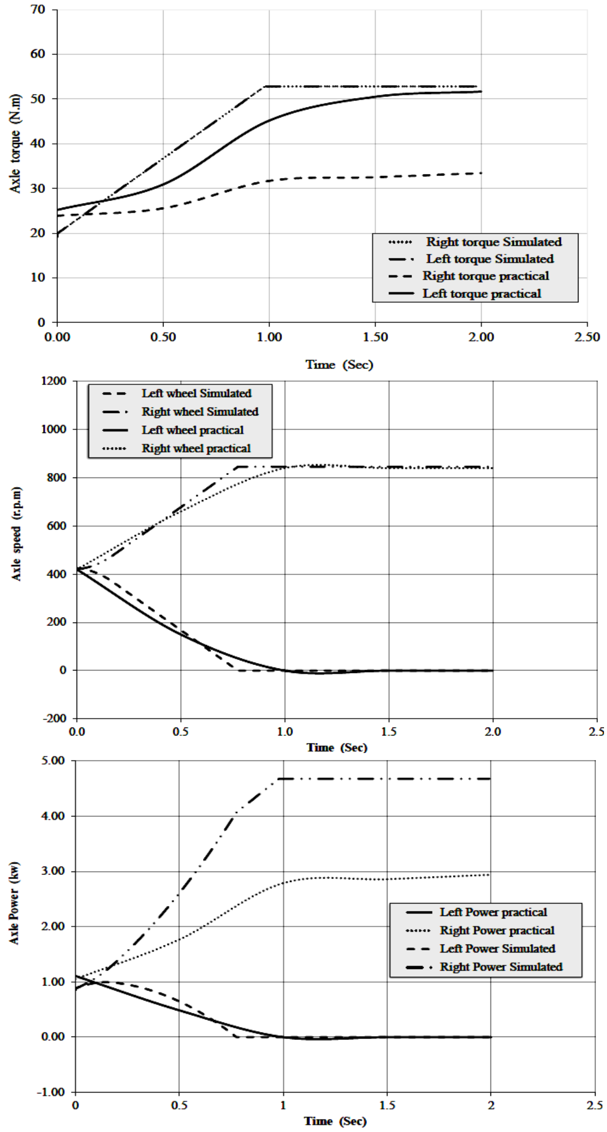


Fig. 12: Axle speed, torque and power without activating controllable device for 2nd step

5.2. Simulation results of active open differential

Figs. 13 to 14 show the torque, rotational speed and, power at left and right wheels respectively for simulink model compared against test rig results with modulated force on the multi-plate clutches when moving on split-adhesion surfaces. All simulated results have same profile as the experimental results. Therefore, the model is acceptable and can be used in analysis of a full car model to predict the vehicle performance on different road adhesion conditions and that the controllable clutch device for torque biasing on split roads.

5.3. Full car simulation model with open differential

To represent the effect of controlled differential on vehicle performance, the test procedure was conducted in the following three scenarios:

- Full car with open differential and equal side road adhesion.
- Full car with open differential and split adhesion.
- Full car with controlled differential and split adhesion.

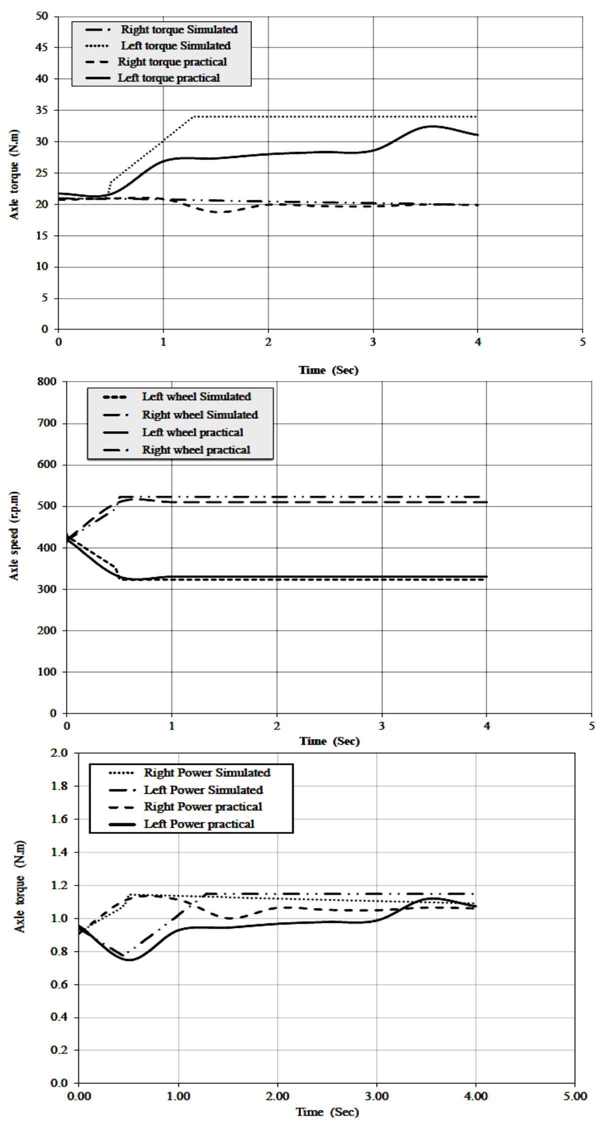


Fig. 13: Axle speed, torque and power with activating the controllable device 1st step

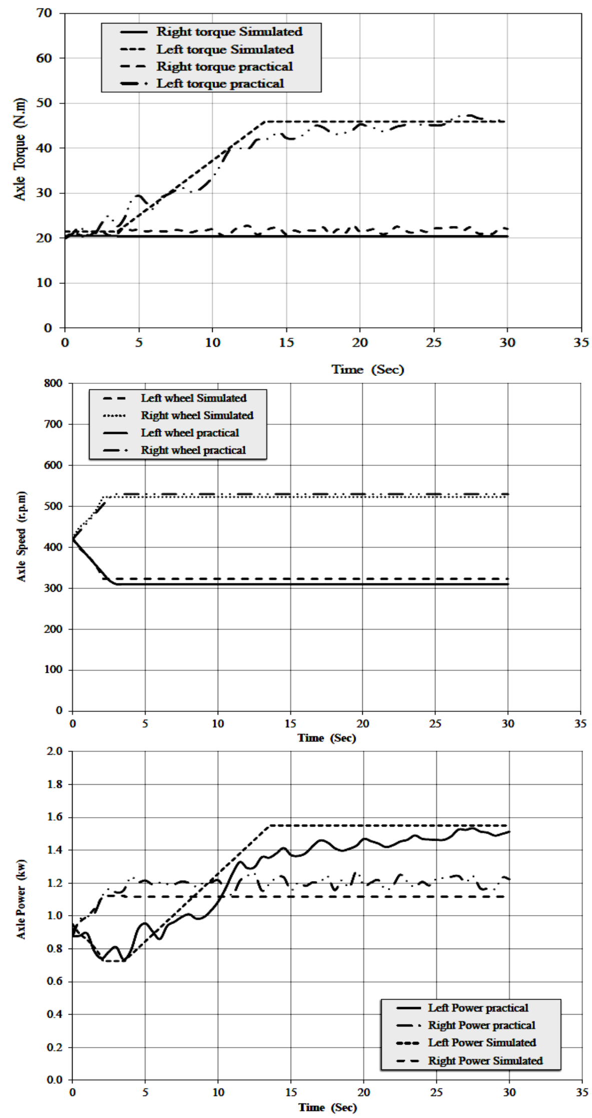


Fig. 14: Axle speed, torque and power with activating the controllable device for 2nd step

5.3.1. Full car with open differential and equal side road adhesion

The speed and torque on each wheel on rear axle are shown in Fig. 15. Vehicle takes 30 seconds to reach its steady state conditions. The traction force and power distributed to each wheel are shown in Fig. 16. When no different resistance applied on the wheels, the speed and torque are distributed equally.

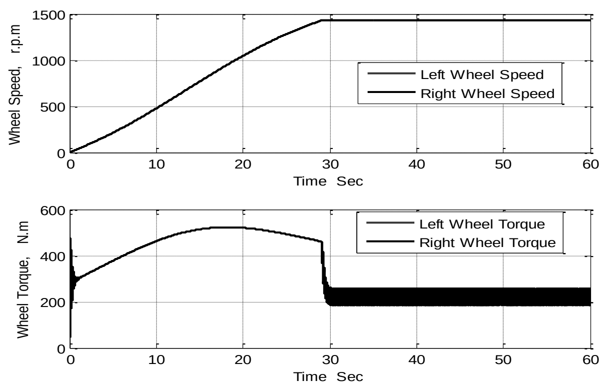


Fig. 15: Speed and torque for each wheel on rear axle with open differential

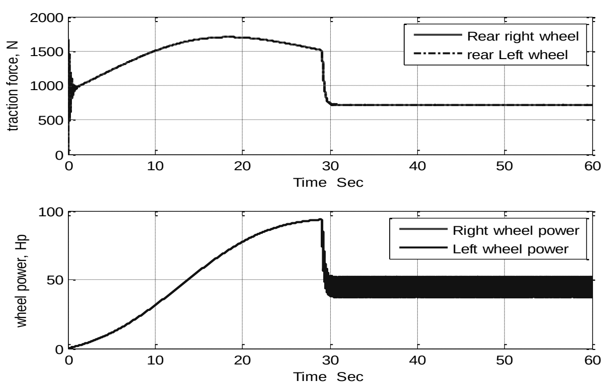


Fig. 16: Traction force and power distributed to each wheel with open differential

5.3.2. Full car with open differential and split adhesion

In these tests the brake was applied (after 30seconds from the beginning at the start of steady state) to the right wheel to simulate effect of different road adhesion on the performance of vehicle with open differential. Figs. 17 and 18 show the car speed, the torque distribution, the traction force and the power on each car wheel. When the resistance on the right wheel is increased for the simulated high road adhesion, the speed of left wheel increases with equal torque on each side. The vehicle speed decreases due to increase in the resistance on the driving axle.

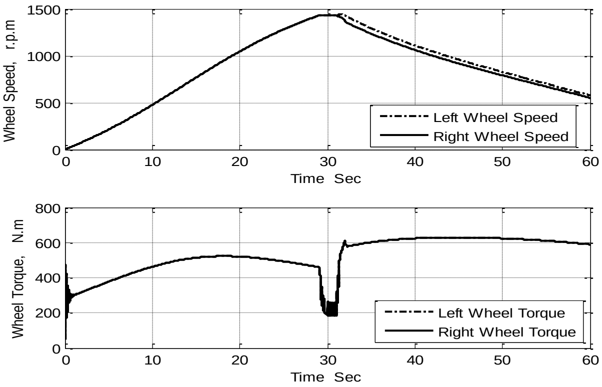


Fig. 17: Speed and torque for each wheel on rear axle for open differential on split adhesion road

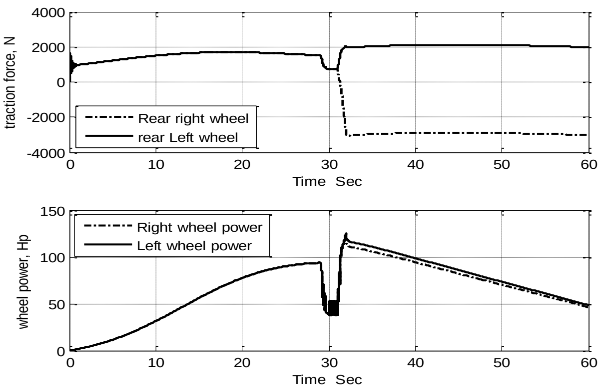


Fig. 18: Traction force and power distributed to each wheel for open differential on split adhesion road

5.3.3. Full car with controlled differential and split adhesion

In this test, the brake was applied as the previous test (after 30 seconds from the beginning at the start of steady state) to the right wheel to simulate different resistances on wheels to represent the effect of different road adhesion on performance of vehicle with open differentials. Figs. 19 and 20 show the vehicle speed, the speed and torque distribution, the traction force, the power and speed with torque difference on each wheel. The resistance on right wheel increases as high road adhesion is simulated, the speed of left wheel increases due to decrease of right wheel speed, and as a result of controllable clutch activation, the torque is increased. The vehicle speed decreases due to increase in the resistance on the driving axle. From Fig. 19 it is noticed that the torque is distributed between the left and right wheels due to activating the controllable clutch on left wheel because its speed is more than the right wheel. During the time period from 32 to 35 seconds, a big speed difference between the two wheels occurs due to activation of clutch control and the torque on left wheel decreases. The control system continues in activating and deactivating the controllable clutch according to the adjustable value of speed difference.

By comparing the results in Figs. 16 and 20, it can be seen that the power on the left side slipping wheel has a value nearly close to the right wheel when clutch system is not activated. When activating the controllable clutch mechanism, there is a power difference between left and right sides; and that means there is a power saving due to the use of a controllable clutch mechanism. This action permits the wheel on high traction to take off the vehicle from the immobilized situation.

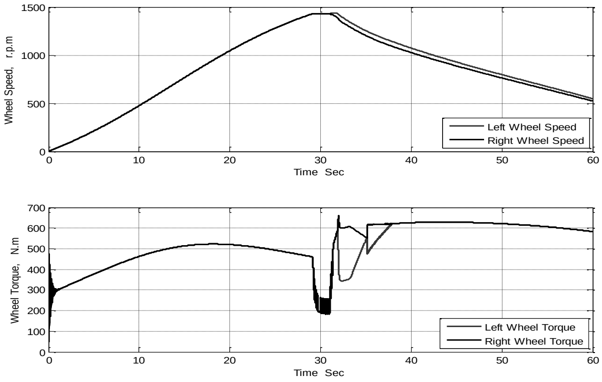


Fig. 19: Speed and torque for each wheel on rear axle for controlled differential on split adhesion road

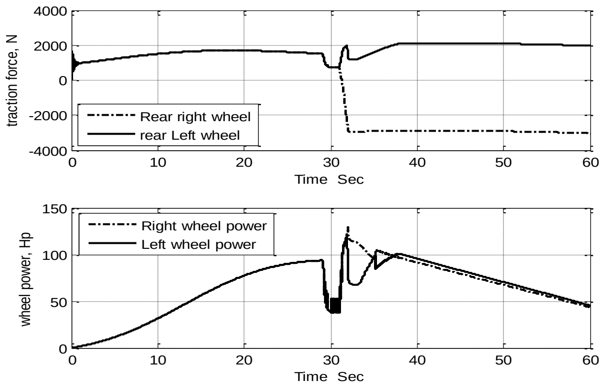


Fig. 20: Traction force and power distributed to each wheel for controlled differential on split adhesion road

6. Conclusion

The proposed SIMULINK model for torque distribution between car wheels on same axle, that has a normal differential with controllable clutch, has been validated with experimental result obtained from a laboratory test rig. This ensures that the conformity between the proposed simulation model and the experimental results. The model has been extended to a full car to predict the car performance on split adhesion. The obtained results showed that the MATLAB simulink modeling is suitable for simulating the proposed controlled device to validate the experimental results of torque distribution between the wheels on vehicle same axle when operating on split adhesion conditions.

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