Model-based Fault Detection and Diagnosis of the Anti-lock Breaking System

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Abstract

The ABS is one of the latest improvements to the braking system, which prevent the vehicle's brakes from locking up and skidding during hard stops on icy or wet roads. ABS controllers are characterized by robust adaptive behaviour with respect to highly uncertain tyre characteristics and fast changing road surface properties. Performance improvement is typically sought in the areas of stability, steerability and stopping distance. In this paper, a non-linear mathematical model of the ABS is developed and ABS system is modelled using Simulink and some of the results are displayed which demonstrate the potential of the proposed model-based prognostics approach.

Key words: Fault diagnosis, model based approach, anti-lock braking system, ABS

Introduction

Due to the increasing demands for higher performance and quality on the one hand and more cost efficiency on the other hand, the complexity and degree of automation of technical processes are continuously growing. Along with this development, the need for more safety and reliability is growing more and more. Model-based fault diagnosis in automated processes has been receiving a considerable attention since the beginning of 1970' [1]. Several survey papers [2, 3, 4, and 5] have explained this clearly. There are many methods mentioned in the literature, which is based on the use of analytical models of the monitored systems [6, and 7]. Some books have been published recently on model-based fault diagnosis. However, when reading these books and literature, one may come to the conclusion that: For years, a model-based diagnostic approach has made much progress in theoretical research and the application of this approach is still not as popular as expected.

Elshanti [8] has dispelled the rumours about model-based diagnostics by providing an illustrator on a control system. This is explained and described in chapter three in that thesis in which most frequent questions about this approach application have been answered. In this paper, a non-linear mathematical model of the anti-lock braking system (ABS) is developed. The novelty is that some faults of ABS are modelled using first principle descriptions and simulated using Matlab/Simulink software. By using these models, model-based fault prediction and prognostics are carried out and some useful information such as ABS fault symptom is provided. The results demonstrate the potential of the proposed model-based prognostics.

Non-linear mathematical model of a one wheel ABS system

Figure 1 shows the structure of a one-wheel anti-lock braking system. In this paper, the mathematical model is developed following its operation procedure.

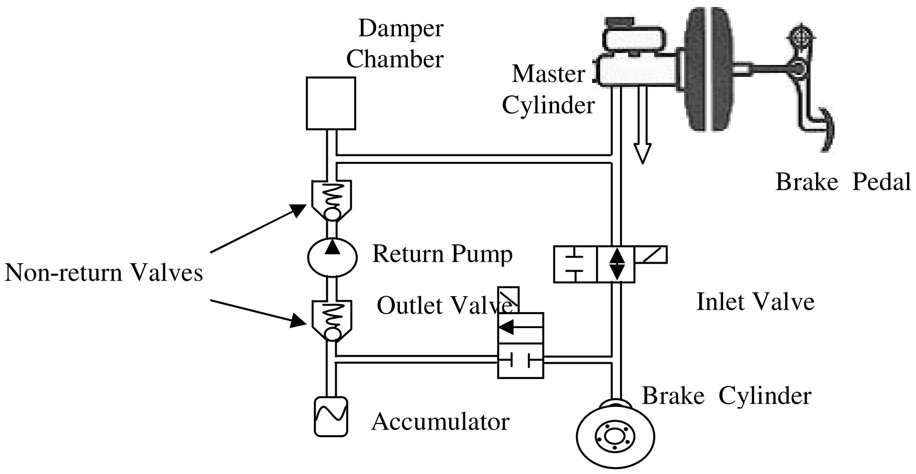
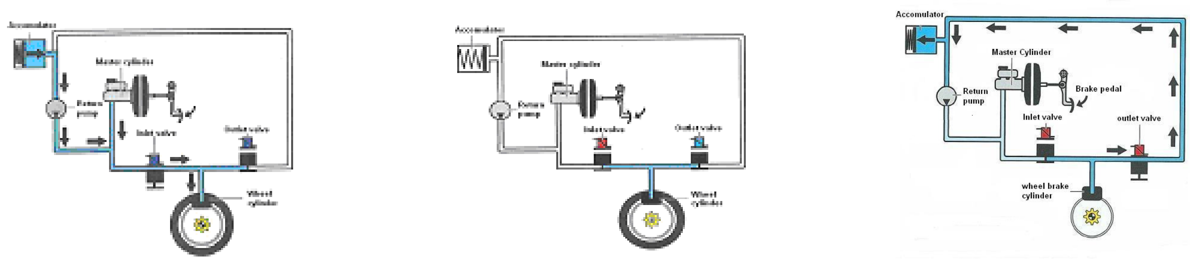


Figure 1: The hydraulic unit of the ABS (one wheel)

In hazardous driving situations, it is possible for the vehicle wheels to lock up while braking. The expected causes of this matter are wet or slippery road surfaces and the driver abrupt reaction of the driver in unexpected hazard. In these cases the vehicle become uncontrollable and may go into a slip or come out of the road. The ABS detects if one or more wheels are about to lock and makes sure that the brake pressure for that wheel or wheels remains constant or reduced. By taking this action, it prevents the wheels from locking up and the vehicle remains steerable. As a result the vehicle can be stopped quickly and safely [9].

The braking procedure of an ABS is usually divided into three stages as shown in figure 2: pressure build up (inlet valve open, outlet valve close) figure 2a, pressure hold on (both valves close), figure 2b, and pressure reduction (outlet valve open and inlet valve close) figure 2c.



(a) (b) (c)

Figure 2: The ABS braking procedure stages

These three stages are controlled by an ECU according to the slip rate requirement as shown in equation (1).

$$S = \frac{V_v - V_w}{V_v} \tag{1}$$

where S is the slip rate, V_v the velocity of the vehicle and V_w the speed of the wheel.

One wheel ABS model

The overall model of the ABS can be obtained by integrating the models developed for the three stages mentioned above. It can then be converted into Simulink for simulation. Figure 3 shows the non-linear model of the ABS under normal condition.

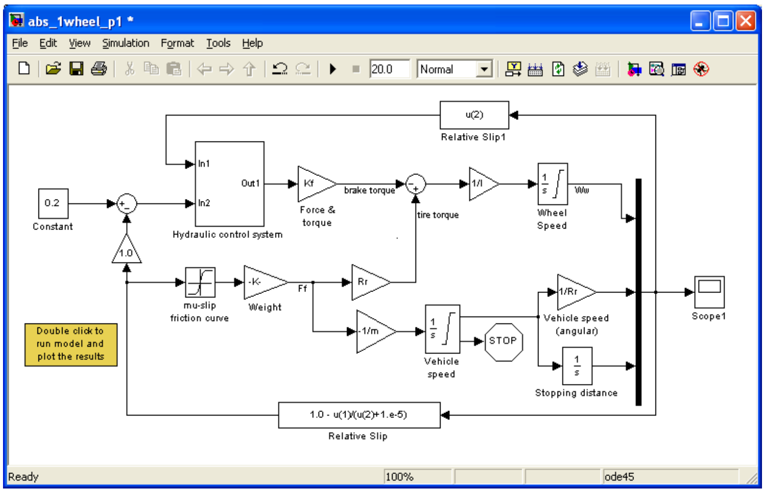


Figure 3: The non-linear model of the one wheel ABS in Simulink

The ECU control strategy that determines the state of brake pressure is modelled with simulink software. The hydraulic unit is masked in a subsystem containing models developed above. Some scopes are designed to view different parameters that are concerned for fault detection. The overall ABS model is displayed in figure 4 below.

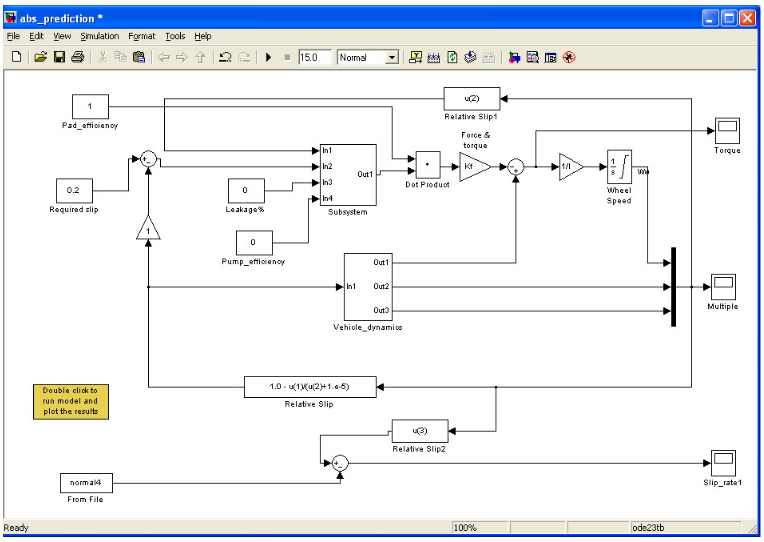


Figure 4: The ABS overall model

Fault modelling of the ABS system

Although there is a self test in ABS, this test usually examines the electrical circuit instead of mechanical performance. It will be a disaster if the ABS passes the self-test but failure for mechanical reasons because the ABS is only used in emergency and the driver never realises the failure is existing in this case. In order to provide fault prediction and prognosis, different types of ABS faults are modelled in this report. They are pump efficiency loss, fluid leakage, oil air blister inclusion and brake pad efficiency loss, all of which exclude electrical failure assuming that those failures can be detected in self-test procedure.

If the pump is completely stocked, it won't return oil back to master cylinder although the ECU tries to control it to do so. In this case, the oil from the brake cylinder can only goes into the accumulator during the ABS course. This is modelled as:

$$Q_p = 0 \tag{2}$$

In practice, however, the pump fails very rear. What happens most frequently in the pump is that the pump efficiency decreases with the age of using. In this case, the oil that is charged into the accumulator cannot be returned to the master cylinder completely and a small mount of oil is left in each of the pressure reduction stage. In addition, because the pressure reduction cannot be completed, the following pressure build-up stage will also be slowed down. The accumulator will sooner or later reach its limitation and fail the pressure reduction. Suppose that the pump efficiency is η, and the theoretical flow rate is Q_0, the returned flow rate will be:

$$Q_p = (1-\eta)Q_0 \tag{3}$$

The pump efficiency loss faults are modelled in Simulink as shown in Figure 5. A switch is used to simulate perfect condition (100%) and failure condition (0%). An input port is used to feed different contents of pump efficiencies. The input port is connected to the overall system panel in convenient to use.

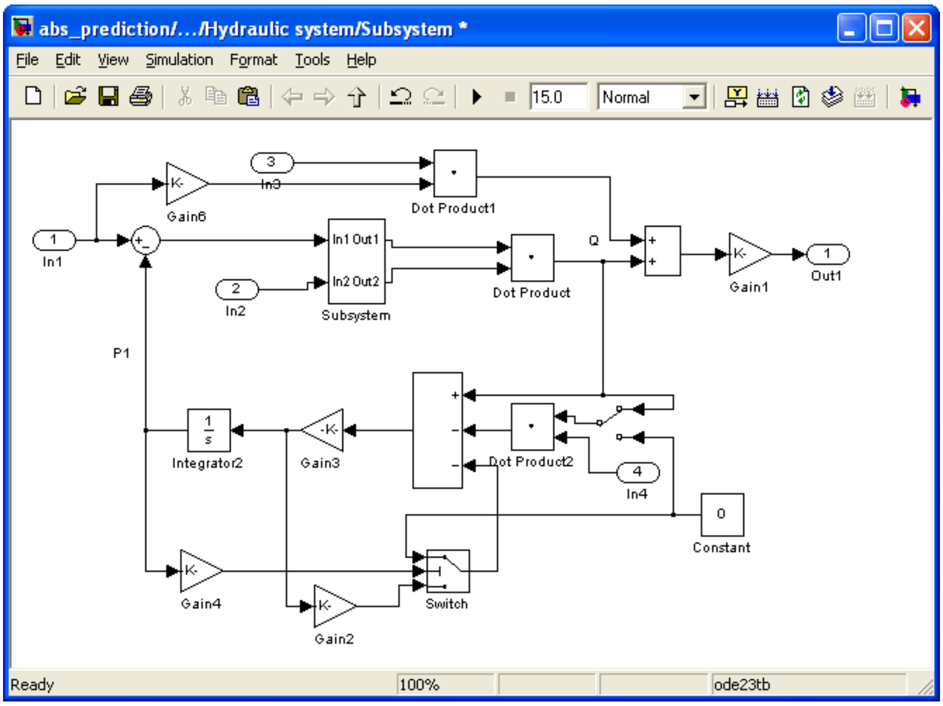


Figure 5: Modelling and Simulation of pump efficiency loss

The leakage in the hydraulic circuit of an ABS may occur in two locations: the pipe between master cylinder to the hydraulic modulator unit and the hose that connects to the modulator to the brake cylinder. The risk of hose leakage is much higher than that of a metal pipe. Therefore, the leakage modelling in this paper is focused only on the hose leakage. When leakage occurs, the leakage flow rate ΔQ is determined by the size of the hole and the pressure inside the cylinder.

$$\Delta Q = C_d R \sqrt{p} \tag{4}$$

Where R is the discharge coefficient. This coefficient describes the size and also the severity of the leakage. If R is small, brake pressure may be decrease for it but can be compensated by the ECU control. If R is large, the brake pressure cannot be built up and the ABS will fail completely.

A brake pad may perform poorly due to overheat or wet pad etc. This poor performance will cause lower torque under the same pressure as normal. This can be represented using a changeable gain in the mathematical model. This model is shown in Figure 4, in which the pad efficiency is entered into the model by percentage.

Model-based fault prognostics

A model-based approach compares the model estimation and the real behaviour of a system and detects fault by analysing the difference between them. This approach can be extended and applied for system estimation and fault prediction as well as fault prognosis. In this paper, it is used for ABS system identification and prognosis.

The model simulation also provides a way to identify the starting points of valve operations. From Figure 5, it can be found that when the inlet valve is turned on, the pressure goes up and down when the outlet valve is turned on. This means that the turn point in the pressure signal is the starting point of a valve when turned on or off. This is easy to be identified if a brake pressure signal is available. In most cases however, there is no pressure sensor installed and therefore the brake pressure signal is not available. In these cases, the starting points can still be identified by analysing the slip rate signal. Figure 5 reveals that when the pressure starts to increase or decrease the second order differential of the slip rate is zero. Therefore, the starting points of the valve operation can be identified by obtaining the zero points in the second order differential signal of the slip rate.

Fault prediction

In order to use model-based approach, the normal condition is simulated. Figure 6 shows the slip rate with respect to time. The starting speed of the vehicle is 64 km/h and the requested slip rate is 0.2 and the curve oscillated about this value.

There are 12 peak counts and the wheel is locked at the time of 3.4 second. Figure 6 shows the stop distance with respect to time. The vehicle stops at the time of 3.5 second and the overall distance is 34.5 m, which is a little bit less than that which is required in the Highway Code. These two signals are used as references and compared to those signals under different conditions.

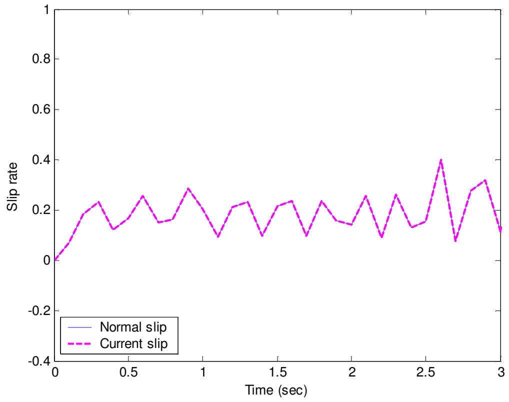


Figure 6: Slip rate under normal condition

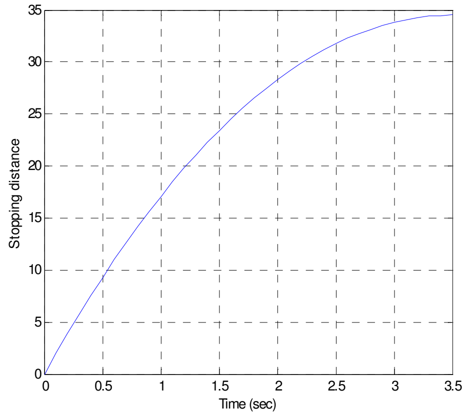


Figure 7: Stop distance under normal condition

Pump efficiency loss

Simulation results of different percentage of pump efficiencies are shown in the flowing figures. Figure 8 shows the simulation results of pump efficiency in 99%, comparing with that of a normal condition (100%). Obviously, the periods from peak to peak are different from that under normal condition and therefore the time relevant residual is meaning less in this signal. , However, the peak counts can be used for model-based approach.

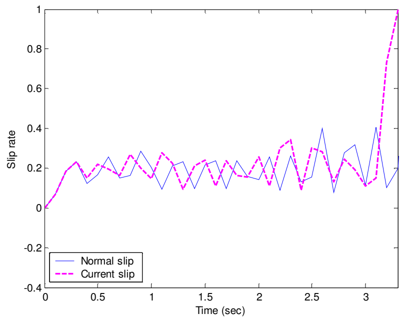


Figure 8: Slip rate under pump efficiency of 99%

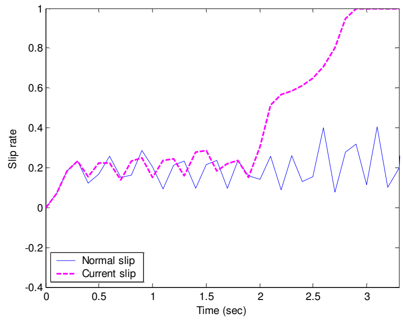


Figure 9: Slip rate under the pump efficiency of 95%

The number of peak counts is 1 less than normal. This shows a trend in performance decrease. Figure 9 shows the slip rate under a 5% efficiency loss. Obviously, there are 5 peak counts less and the wheel is locked 0.5 seconds earlier. Many other efficiency losses can be simulated with the Simulink model. The model-based approach can also be applied using distance signal with respect to time. Because one important purpose of using an ABS is to reduce the stopping distance, the stopping distance with respect to time is an important reflection of the ABS performance. Theoretically, the stopping distance will increase as the pump efficiency decrease.

Fluid leakage

When the hose leaks, it affects the ABS performance in both pressure build-up stage and pressure reduction stage. Besides, the pressure cannot be hold up and even worse the pressure cannot build up at all. Different leakage severities are simulated and the fault symptoms are predicted below. The normal performances are the same as that shown in Figures 6 and 7. Figure 10 shows the performance under 1% leakage, the peak counts are the same as normal. On the other hand, Figure 11 shows that the stop distance with respect to time changes slightly but far from the threshold. This insignificance in stopping distance change maintains until the leakage reaches up to 20%, when the pressure cannot be built up effectively. The slip rate shows the same conclusion although the fluctuation amplitude becomes smaller as the leakage becomes more seriously. However, the pressure signal shows some symptom when leakage occurs.

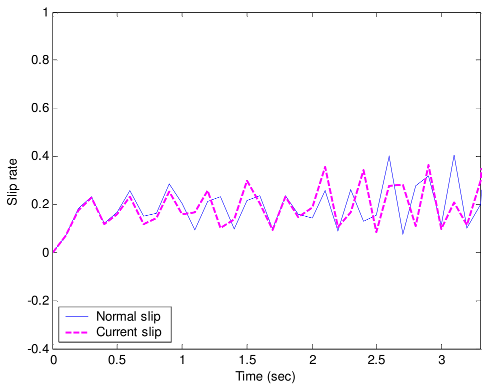


Figure 10: Slip rate under 1% leakage

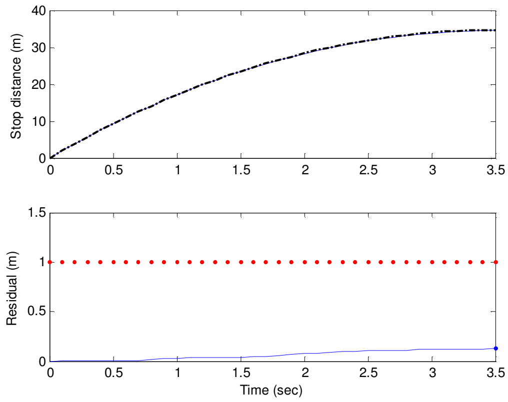


Figure 11: stopping distance under 1% leakage

Figures 12 and 13 show the slip rate and the stopping distance under a 20% leakage. It can be found that there is no lock at all. However, the pressure signal as shown in Figure 14 reveals that the pressure cannot be built up effectively. The more the leakage is, the less is the pressure. The slip rate is lower but the brake is gone!

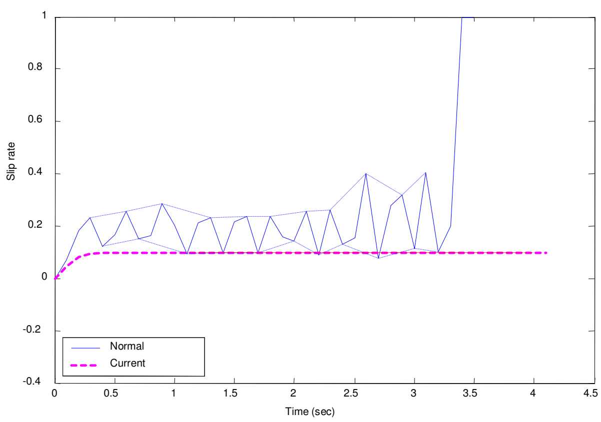


Figure 12: Slip rate under a 20% leakage

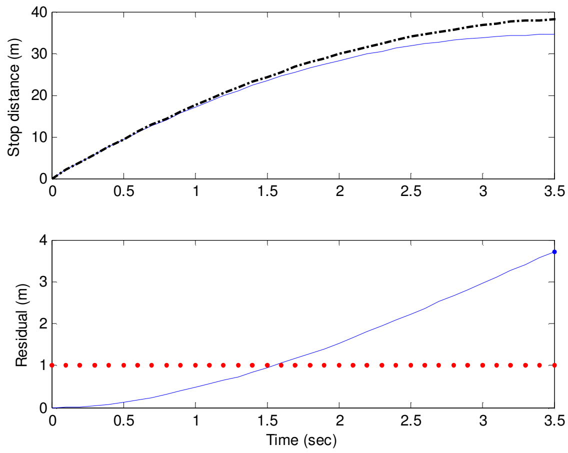


Figure 13: Stopping distance under 20% leakage

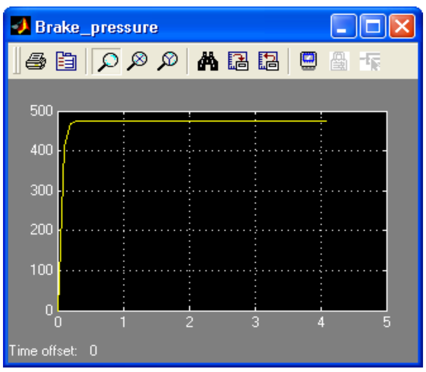


Figure 14: Pressure signal under a 20% leakage

Brake pad efficiency loss

If the brake pad has a poor performance, the brake torque will be affected. This situation is simulated using the ABS model in Simulink. Figure 15 shows the simulation results for different efficiencies of brake pad. It can be found that the peak counts sustain until the pad looses half of its efficiency. The possible reason is that the pad efficiency loss can be compensated by the brake pressure. This compensation, however, will disappear after the pressure reaches its maximum value, when the brake torque will be insufficient and the vehicle will lose brake control.

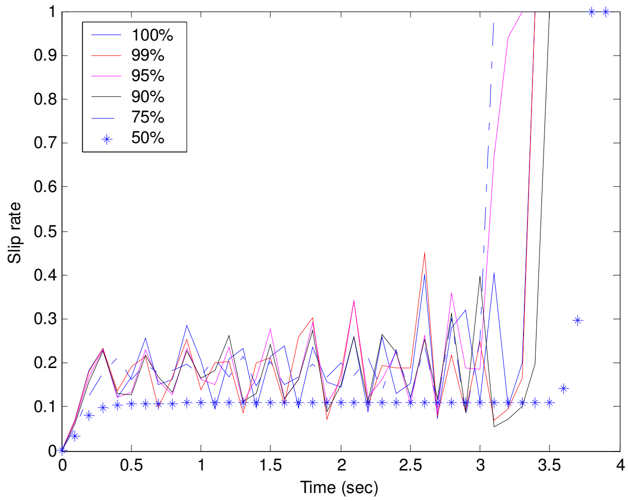


Figure 15: Slip rate under different efficiencies of the brake pad

Air blister in brake fluid

If air blister exists in the brake fluid, the bulk modulus will decrease significantly. This significance may be 5 or 10 times less. Therefore, some changes in bulk modulus are used in the simulation of air blister inclusion. As shown in Figure 16, if the bulk modulus decreases by 2 times, the peak counts will be less by 4 than normal counts. In addition, the slip rate goes up slower than normal. This symptom is also detected in the stopping distance residual as shown in Figure 17 in which the residual exceeds the given threshold. The fault symptom is more obvious when more air blister is contained in the fluid.

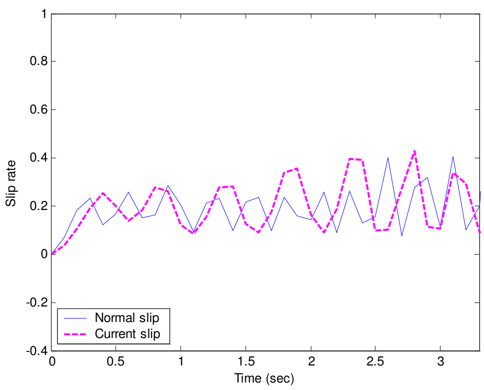


Figure 16: Slip rate under air blister inclusion

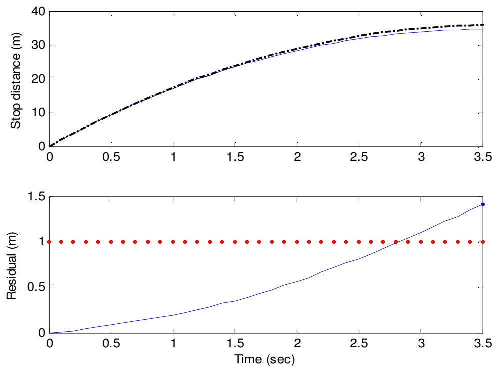


Figure 17: The stopping distance under air blister condition

Figure 18 shows the slip rate when bulk modulus decreases by 10 times. It can be found that the more air blister contains in the brake fluid the slower the slip rate reaches the required value and the less is the oscillation peaks counts. The distinguished symptom of the air blister inclusion is that the slip rate increases quite slowly even in the starting period, which doesn't happen in other fault symptoms.

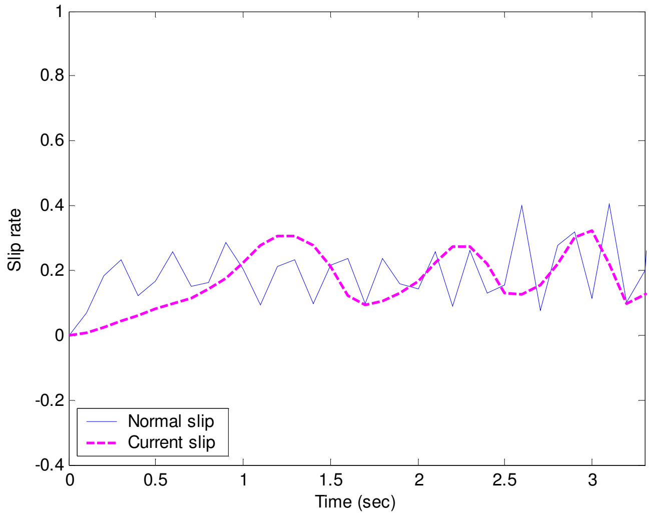


Figure 18: Slip rate under air blister condition

Model-based fault prognostics

While diagnostics is the technique concerned with detection, identification the faults or malfunction in the system and its subsystems, prognostics is any technique that provide early detection and isolation of incipient fault and prevent failure of a system or its components. Using model-based approach, the incipient fault can be predicted by examining the residual between the real system behaviour and the model prediction. As discussed above, the ABS model developed in this thesis is mainly for pump efficiency loss and hose leakage faults. Figure 8 indicated that the model-based approach with the slip rate signal is sensitive to 1% pump efficiency loss. The simulation results for leakage faults show that the pressure signal is effective to the incipient fault that occurs in the hydraulic system. Its fluctuating amplitude and its details in the transient period can be used for fault signature. This raises a requirement that the pressure signal of the brake cylinder should be measurable. Fortunately, such type of sensor has been installed into the new generation of vehicles. Nevertheless, the slip rate and the stopping distance will be sensitive if the leakage reaches 20%. This approach is also sensitive to air blister inclusion. Although an accurate influence of air blister to the decrease of bulk modulus is not clear at the moment, it is obvious that the slip rate and the stopping distance are sensitive to those bulk modulus changes. The sensitivity of this approach to pad efficiency loss is not as obvious as those of pump efficiency losses. This is because the brake pressure will compensate some content of pad efficiency loss by a closed loop ECU control. This suggests that the pad should be monitored separately from the ABS system.

Conclusions and future work

In the last period, we developed a non-linear model of the ABS and simulated it in Simulink. The model-based strategy is also used in the ABS fault prediction and prognostics. The following conclusions can be drawn from this development. Firstly, the ABS model can be developed using first principle function and equations. Secondly, the model-based approach is sensitive to some incipient faults that may occur in an ABS. Although the sensitivity is different from fault to fault, the success of this development provides an effective technique for prognostics of vehicle systems. The development raises some new requirements in the measurement of the system. Pressure signal is a very important parameter for model-based prognostics. Torque and pedal travel are also very helpful if they can be measured. Finally, some publications can be prepared based on the ABS modelling and model-based prognostics. The next step will focus on the calibration of the model developed. This relies on the real measurements of the ABS behaviour of the test rig which we will work on. After that a model-based ABS prognostic can be implemented.

References

1. **Jones, H. L.** ***Failure detection in linear systems,*** **PhD thesis, Dept. of Aeronautics, MIT, Cambridge, Mass, 1973**
2. **Frank, P. M.** ***Advances in observer-based fault diagnosis.*** **Proc. TOOLDIAG'93, pages 817-836, Toulouse, France, 1993 CERT.**
3. **Patton, R. J.** ***Robust model-based fault diagnosis: the state of art.*** **IFAC Fault Detection, supervision and safety for Technical Processes, pages 11-24, Espoo, Finland, 1994**
4. **Gertler, J. and Costin, M.** ***Model-based fault diagnosis of automotive engines.*** **IFAC Fault Detection, Supervision and Safety for Technical processes, pages 393-402, Espoo, Finland, 1994**
5. **J Chen, Ron J. Ptton,** ***Robust model based fault diagnosis for dynamic systems*****, Kluwer Academic Publisher, London, 1999**
6. **Press, China, 1999**
7. **Willsky, A. S,** ***A survey of design methods for failure detection systems,*** **Automatica, 1976, Vol. 12, pp 601-611**
8. **El-Shanti Ali Hassan,** ***The Model Based Condition Monitoring of Electro-hydraulic Servo Systems,*** **Mphil. thesis, Manchester School of Engineering, 2002**
9. **R. Bosch GmbH,** ***Conventional and Electronic Braking Systems*****, Robert Bosch GmbH Publisher, Postfach, 2003**