Solenoid Valve Diagnosis for Railway Braking Systems with Embedded Sensor Signals and Physical Interpretation

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ABSTRACT

This paper proposes a fault diagnosis method for solenoid valves in urban railway braking systems. For dominant failure modes of solenoid valves, sensor signals including electrical current, and input and output pressure were acquired and analyzed. The physical behaviors of the solenoid valves are modeled analytically. Numerous forces including magnetic, elastic, and gravity forces are incorporated in the model. With the analytical model and sensor signals, health indices are defined. The health indices are used to quantify the condition of the solenoid valves with different failure modes. Finally, a fault diagnosis method is proposed with the health indices and failure criteria. We anticipate that this study can help decrease maintenance costs and improve reliability of urban railway braking systems.

1. INTRODUCTION

Urban railway vehicles become popular in metropolitan areas for low-carbon emission and realization of green growth. Nonetheless, if railway vehicles derail or crash, it can cause severe loss on human lives and economy. For instance, in December 2009, a Croatia commuter train crashed into the platform in Zagreb that led to the injury of about 60 people. On July 23, 2011, the train D301 crashed with the train D3115 in China, causing 172 injuries and 193 million yuan loss. Because of the fatalness of railway vehicle accidents, lots of efforts were put to prevent accidents in advance.

To ensure safety and reliability of urban railway braking system, two approaches including fault avoidance and removal, and fault tolerance have been used widely (Isermann, 2006). The purpose of the fault avoidance and removal is to lower failure rates during design stage. Although the approach is effective, it is infeasible to identify and remove all the potential failures during the design stage. To tolerate faults during operation, the concept of redundancy was adopted. When a single component of braking systems does not operate as intended, the braking system can perform normally with the use of a redundant component. However, with the increased number of redundancy, the cost of the system becomes higher. Therefore, the number of redundancy should be minimized.

Recently, the concept of condition-based maintenance (CBM) approach was proposed to overcome the limitations of the conventional approaches. The CBM approach identifies the condition of the system and makes a maintenance decision based on the current condition. The key techniques for CBM are how to detect, isolate and identify the root cause of faults (Yang & Widodo, 2009). According to the study by Ma (1997), if the CBM is adopted on rail freight vehicles, the lifecycle cost can be reduced up to 12%.

In this paper, a fault diagnostic method is proposed to enable the CBM of urban railway braking systems. According to the previous study (Seo, Lee, Jo, Oh, and Youn, 2016), the most relevant component for the CBM of urban railway braking systems was reported to be solenoid valves. Dominant failure modes of the solenoid valves are shown in Table 1: (1) burnout of the solenoid coil, (2) accumulation of debris, and (3) valve seat damage. With the background knowledge about the dominant failure modes, we attempted to develop an efficient fault diagnostic methods for solenoid valves in urban railway braking system. The remaining of the paper is organized as follows. In Section 2, a literature review is shown on fault diagnosis of solenoid valves. In Section 3, an experimental setup is presented to collect the sensor signals from normal and faulty solenoid valves. In Section 4, a fault diagnostic method for the solenoid valves is proposed by considering the physical behavior of the solenoid valves. Section 5 concludes the study and shows future works.

Table 1. Failure analysis of solenoid valves

Item	Function	Failure Mode	Failure Cause	Failure Effect		
				Corresponding Item	Upper Item	Vehicle
Solenoid Coil	Control of valve stem behavior	Burnout	Temperature rise	Abnormality of valve stem behavior	Unnecessary exhaust	Disability of braking force
Supply Valve	Control of air flow	Accumulation of debris	Impurities from other components or air	Abnormality of supply valve behavior	Lack of standard pressure	lack of braking force
		Rubber damage	Fatigue failure by valve stem impact	Supply valve jamming	Disability of supply or exhaust of compressed air	Disability of braking force

2. REVIEW OF FAULT DIAGNOSIS OF SOLENOID VALVES

Solenoid valves are the main component to control the operation of pneumatic and hydraulic systems in various applications. Fluid flow systems are connected each other. If the one of the systems are broken, the whole system is affected. To avoid valve faults in the systems, several studies were conducted. In this section, a literature review is shown on the fault diagnostics of solenoid valves in various applications such as nuclear power plants, fuel injection systems, and anti-lock brake systems in vehicles.

Kryter (1990) found two main factors (coil impedance and current) for fault diagnosis of solenoid valves used in the nuclear generating station. In the case of fault solenoid valves, although the current applied to solenoid coil increases, the impedance is almost constant. Therefore, a valve stem cannot behave normally. Based on this, Kryter used impedance and current of coil as monitoring signals. This method is simple and does not require any additional sensors. But it cannot define a limit of normal and cannot diagnose each failure mode distinctively.

Börner, Straky, Weispfenning, and Isermann (2002) tried to diagnose valve stem stuck in cylinder based on an electro-magnetic model. It estimates the displacement of valve stem. The fault is diagnosed when the difference between the estimated displacement and the armature stroke calculated by a mathematical model of solenoid valves proposed by Straky and Weispfenning (1999) exceeds the limit. This method has a merit that it does not need any additional sensors because it measures the input voltage and current of coil. However, it also has a limitation that it does not include an experiment and only depends on models. Therefore, it is necessary to validate the physical model using test data.

Last, Tsai and Tseng (2010) developed a model based fault diagnosis of solenoid valves used in the diesel fuel injection system. Modeling the displacement of a valve stem mathematically, they found the factors related to failure through experiments. Then, they made a fault classifier using artificial neural networks (ANNs). It seems to be innovative since it reduces the time for extracting the model parameters related to the faults. Nonetheless, the performance of the ANN classifier was evaluated under the simulated operating conditions. It is always desirable to evaluate the diagnostic performance in actual operating conditions.

Several studies proposed fault diagnosis methods for solenoid valves in a variety of industries except the railway industry. The research related to fault diagnosis of railway braking system is still incomplete. Therefore, we tried to develop a fault diagnosis of solenoid valves in railway braking system.

3. EXPERIMENTS

As mentioned in the introduction, the three main failure modes including burnout of solenoid coil, accumulation of debris and valve seat damage are known for the solenoid valves for urban railway braking systems. This section presents a series of experiments with the individual failure modes and sensor signal measurements.

3.1. Experimental Setup

The testbed consists of power supply, air compressor, reservoirs, brake tank, solenoid valves and sensors shown in Figure 1. We received solenoid valves from Seoul Metropolitan Rapid Transit Corporation. Input pressure and output pressure were measured by sensors of Keller that are used in urban railway vehicles virtually.

The voltage control algorithm is constructed to apply the current according to valve position (supply (370 mA), neutral-supply (220 mA), exhaust (50 mA), neutral-exhaust (150 mA)) using LabVIEW. Electrical current, input pressure and output pressure are measured as a monitoring signal.

Data acquisition sampling frequency is set as 10 kHz. Normal data and abnormal data are acquired from five normal valves and one fault valve individually.

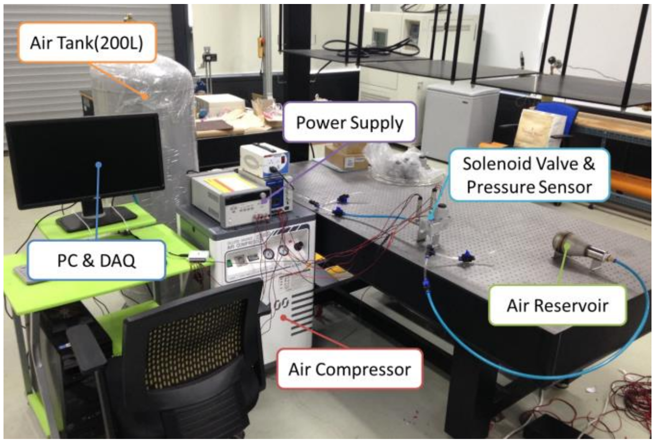


Figure 1. Testbed of solenoid valve in railway braking system

3.2. Results

Data obtained from the testbed are analyzed by each failure mode in this section.

3.2.1. Failure Mode 1: Burnout of Solenoid Coil

As shown in Figure 2, we defined supply current as current valve when the output pressure of valve increases 10%. It is because the movement of plunger stops when the output pressure of valve increases 10%.

If a short occurs locally in solenoid coil and coil burns out from the short, the resistance and inductance are reduced. Therefore, the current value of fault valve would be larger than that of the normal valve for same entire voltage. Experiment results are shown in Figure 3 and it is visible that the supply current of fault valve is higher than any other normal valves.

3.2.2. Failure Mode 2: Debris Accumulation

It is difficult to obtain the fault valve in that the debris is accumulated in the field. Therefore, we artificially applied the debris in the solenoid valve. When debris is accumulated on the valve seat, a gap is generated between valve stem and valve seat and the compressed air moves from input port to exhaust port and then the output pressure decreases as shown in Figure 4.

So, we attached debris on the top of valve seat like Figure 5. Although using a material generated in real field is the most appropriate way, it is difficult to analyze the real material and control the size of debris. With the limitation in mind, steel-shim plates were employed in this study. The size of the shim plates is 2×2 mm^2, while the thickness of the shim plates varies from 0.1 to 1.0 mm with the increment of 0.1 mm.

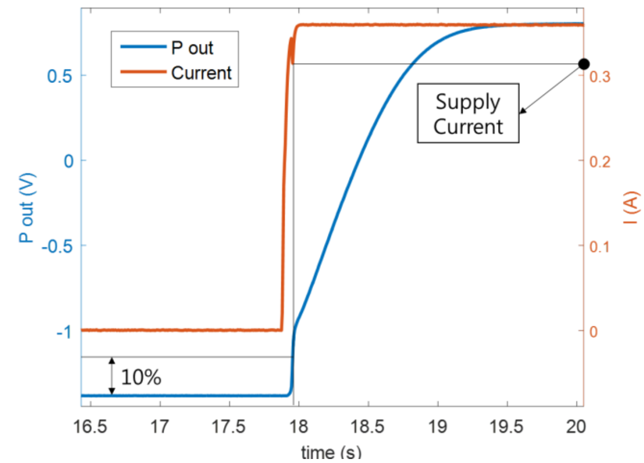


Figure 2. Definition of health index: supply current

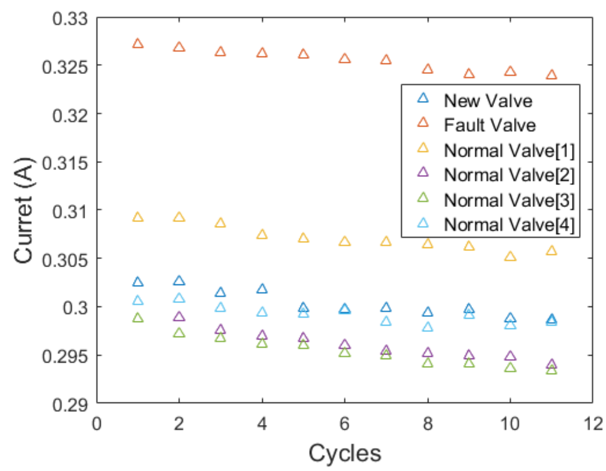


Figure 3. Decrease of supply current according to operating cycles

The solenoid valve is operated 11 cycles at each thickness level. The maximum output pressure at each thickness level was used to develop a health index. As shown in Figure 6, the output pressure reduces as the thickness of debris increases. It is speculated that the reduction is attributed to (1) air leakage by the gap between the valve seat and valve stem and (2) decrease of magnetic force by debris interference. Especially, when the thickness of the debris is larger than 0.3 mm, the magnetic force is one of the dominant factors.

According to the magnetic flux density model proposed by Mutschler, Dwivedia, Kartmanna, Bammesbergera, Koltaya, Zengerle, and Tanguy (2014), the magnetic flux density is the function of distance between plunger and solenoid coil show in Eq. (1).

$$B(z) = \frac{\mu_0 NI}{2L_{\text{coil}}}\left(-\frac{z-\frac{L_{\text{coil}}}{2}}{\left(\left(z-\frac{L_{\text{coil}}}{2}\right)^2+R_{\text{coil}}^2\right)^{\frac{1}{2}}}+\frac{z+\frac{L_{\text{coil}}}{2}}{\left(\left(z+\frac{L_{\text{coil}}}{2}\right)^2+R_{\text{coil}}^2\right)^{\frac{1}{2}}}\right) \quad (1)$$

If debris is accumulated on the valve seat, the distance will increase and the magnetic flux density will decrease. According to Eq. (15), the magnetic force also reduces and valve cannot move down easily.

$$F_{\mathrm{M}}(z) = \pi M R_{\mathrm{plunger}} \left(-B_{\mathrm{coil}}\Big|_{z-\frac{L_{\mathrm{plunger}}}{2}} + B_{\mathrm{coil}}\Big|_{z+\frac{L_{\mathrm{plunger}}}{2}} \right) \quad (2)$$

As a result, the maximum output pressure looks like the shape of Figure 6.

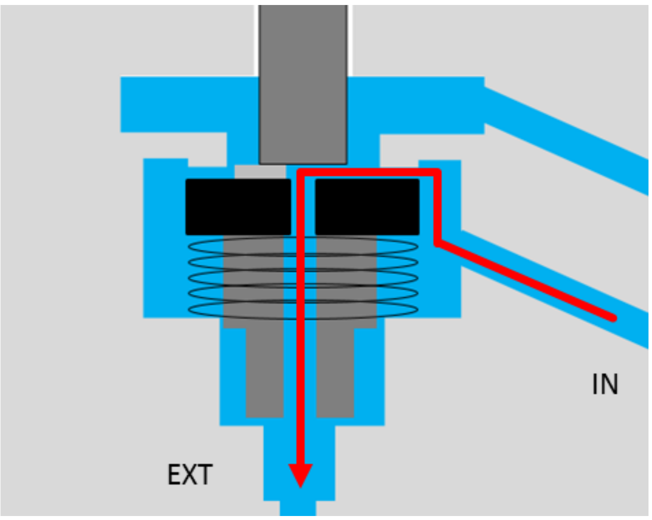


Figure 4. Air flow when debris is accumulated on the valve seat

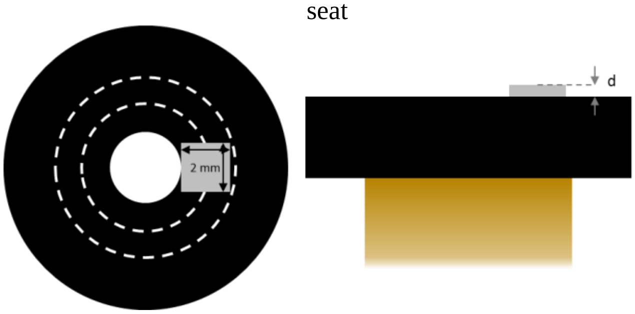


Figure 5. Fault seeding of accumulation of debris

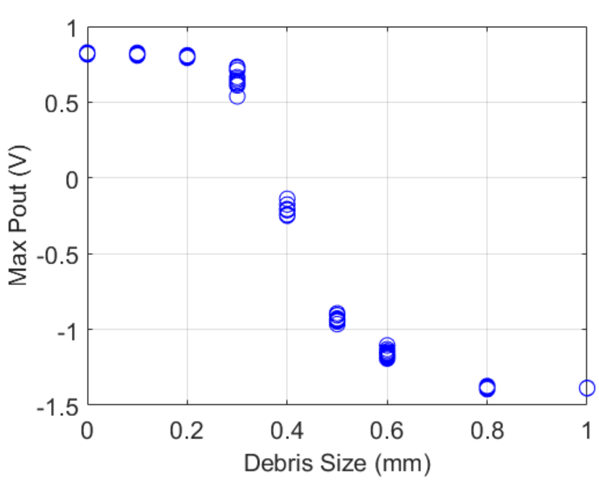
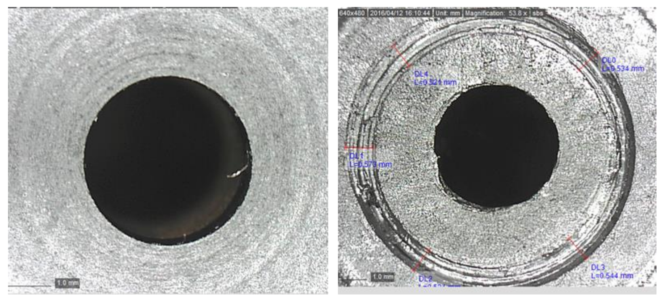


Figure 6. Output pressure reduction according to debris size

3.2.3. Failure Mode 3: Valve Seat Damage

Valve seat is often damaged like Figure 7 by repeatable contact with valve stem. So, there is a difference in input pressure signal between normal and damaged valve. In case of normal valve the input pressure increases at exhaust mode. On the other hand, in case of damaged valve, the leakage of input air occurs at exhaust mode shown in Figure 8. When the valve stem is separated from the valve seat, the valve seat moves down for a short time by reaction force. So, a gap is formed between valve seat and valve structure and input air leaks through the gap.



a) b)

Figure 7. Comparison of normal and damaged valve seat: a) normal and b) damaged valve seat

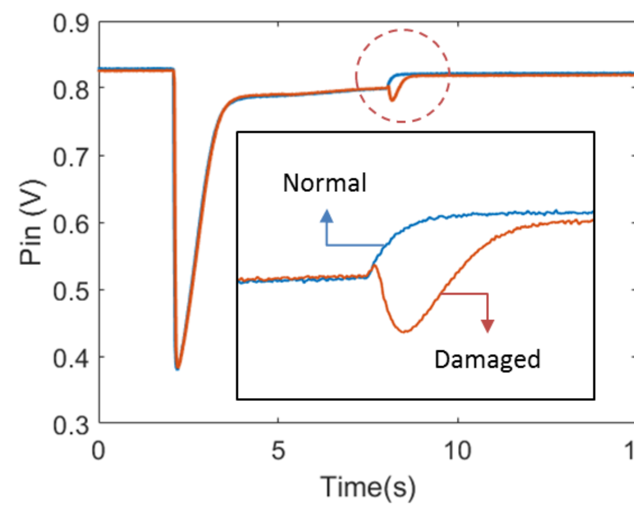


Figure 8. Comparison of input pressure between normal and damaged valves

4. PROPOSED METHOD FOR DIAGNOSING THE RAILWAY BRAKING SOLENOID VALVES

From the experimental results in Section 3.2., we confirmed that it is possible to diagnose the main failure modes of solenoid valves based on two types of signals, current and pressure. Therefore, we propose the fault diagnosis method of solenoid valves according to the type of measured signals in this section.

4.1. Current Based Fault Diagnosis for Solenoid Valves

In Section 3.2, the supply current of fault valve is higher than that of normal valve. As the number of cycle rises, the supply current dwindles gradually. If this state continues, it is difficult to classify the fault valves and normal valves used for a long time. To calibrate the decline of supply current, equivalent circuit model of solenoid valve and the effect of temperature on current are discussed.

Generally, the voltage equation of solenoid valve is well-known as Eq. (3) (Rahman, Cheung, and Lim, 1995).

$$V_{\mathrm{d}} = I(t)(R_{\mathrm{ext}} + R_{\mathrm{int}}) + L\frac{dI}{dt} \tag{3}$$

V_{d} and $I(t)$ are a constant voltage and current in the circuit respectively. Internal resistance of coil and external resistance are indicated as R_{int} and R_{ext} individually. L is constant inductance of solenoid coil. A circuit diagram of solenoid can be schematized like Figure 9. From applying Laplacian transform in Eq. (3), it is derived as Eq. (4) (Kreyszig, 2006).

$$\frac{V_{\mathrm{d}}}{s} = I(s)(R_{\mathrm{ext}} + R_{\mathrm{int}}) + LsI(s) \tag{4}$$

To induce Eq. (4) in terms of $I(s)$, Eq. (5) can be expressed as partial fraction form:

$$I(s) = \frac{V_{\mathrm{d}}}{R_{\mathrm{ext}} + R_{\mathrm{int}}}\left[\frac{1}{s} - \frac{1}{s + \frac{R_{\mathrm{ext}} + R_{\mathrm{int}}}{L}}\right] \tag{5}$$

Through the inverse Laplacian transform in Eq. (5), current can be formulated in time region as Eq. (6).

$$I(t) = \frac{V_{\mathrm{d}}}{R_{\mathrm{ext}} + R_{\mathrm{int}}}\left[1 - e^{-\frac{R_{\mathrm{ext}}+R_{\mathrm{int}}}{L}t}\right] \tag{6}$$

In Eq. (6), because resistance of coil is much larger than inductance of coil, the term of exponential formula converges to zero within very short time. As a results, solenoid current model can be approximated as Eq. (7).

$$I(t) = \frac{V_{\mathrm{d}}}{R_{\mathrm{ext}} + R_{\mathrm{int}}} \tag{7}$$

Internal resistance of coil is sensitive to temperature. From Eq. (7), the current should be altered along the change of internal resistance. If we set that $R_{\mathrm{int,0}}$ is an initial value of resistance and α is a temperature coefficient of resistance, relation between resistance and temperature can be expressed as Eq. (8).

$$\Delta R = \alpha R_{\mathrm{int,0}} \Delta T \tag{8}$$

By Eq. (8), the alteration of current is shown as Eq. (9).

$$\Delta I = \frac{V_{\mathrm{d}}}{R_{\mathrm{ext}} + R_{\mathrm{int,0}} + \Delta R} - \frac{V_{\mathrm{d}}}{R_{\mathrm{ext}} + R_{\mathrm{int,0}}} \tag{9}$$

From substitute Eq. (8) into Eq. (9), the Eq. (10) could be gained.

$$\Delta I = \frac{V_{\mathrm{d}}}{R_{\mathrm{ext}}+R_{\mathrm{int,0}}(1+\alpha\Delta T)} - \frac{V_{\mathrm{d}}}{R_{\mathrm{ext}}+R_{\mathrm{int,0}}} \tag{10}$$

In Eq. (10), variation of current is negative if that of temperature is positive because the temperature coefficient is positive.

We measured the temperature of coil at four locations. Using mean temperature of four locations, we calibrated the supply current by Eq. (10). In the test, R_{ext} is one-hundred times lower than $R_{\mathrm{int,0}}$. Therefore, R_{ext} is ignored. After calibrating the current, we can remove the impact of temperature on the change of the current values. The results are depicted in Figure 10. It is possible to classify the fault and normal valves regardless of operating time. To this end, the supply current is determined to be health index.

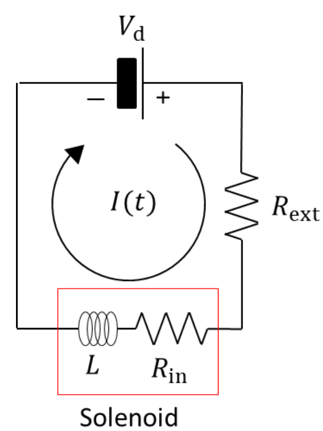


Figure 9. Diagram of solenoid circuit

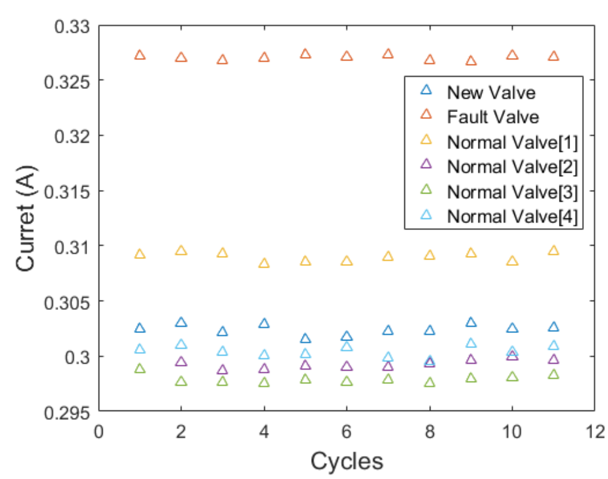


Figure 10. Diagnosis of burnout of solenoid coil (after calibration)

4.2. Pressure Based Fault Diagnosis for Solenoid Valves

As mentioned in Section 3.3, two main failure modes (1) accumulation of debris on valve seat and (2) valve seat damage can be detected using output and input pressure signals.

First, to diagnose the accumulation of debris we developed the regression model between thickness of debris and output pressure from the result in Section 3.3. We used sigmoidal regression model due to the similarity of experimental result and sigmoidal function. General sigmoidal function is expressed as Eq. (11).

$$f_s(x) = \frac{c_1}{c_2 + e^{c_3 x + c_4}} + c_5 \tag{11}$$

We found the model parameters that minimize the model errors and final model is represented as Eq. (12). It is depicted in Figure 11 as red line.

$$g_s(x) = \frac{12.31}{5.616 + e^{17.46x - 5.359}} - 1.347 \tag{12}$$

It is an adequate model that has a high R-square value, 0.9972. Therefore, it is possible to estimate the thickness of debris according to output pressure from this regression model.

Second, to diagnose the valve seat damage, it is important to quantify the variation of input pressure. Therefore, we considered the ratio of P_{min} and P_{ref}. P_{min} is the minimum input pressure at the exhaust mode. P_{ref} is the averaged pressure value when the output pressure is higher than 99% of the maximum output pressure. To amplify the ratio, we used a form of decibel. It is expressed as $10\log(P_{\mathrm{min}}/P_{\mathrm{ref}})$ and we defined it as the health index. When health index is positive, it is normal valve and in opposite case it is damaged valve. The result is shown in Figure 12.

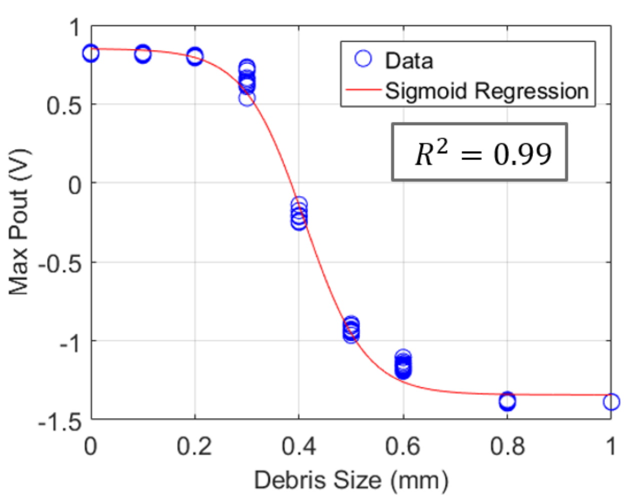


Figure 11. Sigmoidal regression model of accumulation of debris

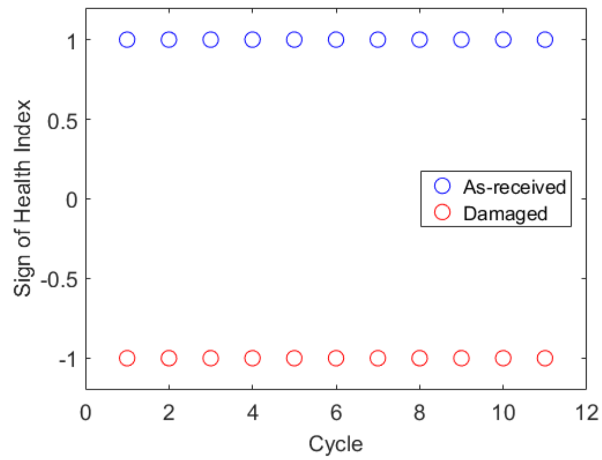


Figure 12. Diagnosis of valve seat damage

5. CONCLUSION

In this paper, a fault diagnosis method was proposed for solenoid valves in urban railway braking systems. An experimental setup was built to test solenoid valves with different failure modes. The physical behaviors of the solenoid valves are modeled analytically. The health indices are used to quantify the condition of the solenoid valves with different failure modes. Finally, a fault diagnosis method was presented with the health indices and failure criteria.

For the detection of burnout of solenoid coil, a health index was determined using the current signal from the power supply. When the health index increases 10% larger than its nominal value, it was determined to be a fault. For the detection of excessive accumulation of debris, the pressure signal from the output was used. The health index was determined to be the maximum value of the output pressure. From the sigmoidal regression model between the health index and thickness of debris, we could estimate the thickness of debris. When the estimated thickness is larger than allowable level, it was determined to be a fault. For the detection of valve seat damage, we only used input pressure signal and extracted a health index as $10\log(P_{\mathrm{min}}/P_{\mathrm{ref}})$. When the health index had a negative value, it was determined to be a damaged valve.

The proposed fault diagnostic method has several advantages over other methods. First, it does not require any placement of additional sensors. It uses existing sensors in the braking system in urban railways. Second, the proposed method provides the integrated solution to diagnose the dominant failure modes of solenoid valves. Last, online fault diagnosis is possible without overhaul of braking systems. In summary, it is anticipated that the study help the railway industry enable the CBM of railway braking systems.

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BIOGRAPHIES

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