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Residual-based Fault Detection Method: Application to Railway Switch & Crossing (S&C) System

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Abstract: This paper proposes a model-based fault detection (FD) method with application to railway switch & crossing (S&C) systems. These systems are safety critical assets in the rail network and they daily exposed to harsh working conditions and severe environment, which make them more vulnerable to failures and breakdowns. Therefore, it is critical to implement a condition monitoring (CM) technique to enhance the reliability and the availability of these S&C systems. To-the-end of reducing the scheduled maintenance process and decreasing the possible number of delays and/or accidents. This paper thus, proposes a simple model-based technique, a modified residual-based technique, which can be implemented in the real rail network for FD with application to railway electro-mechanical switch system.

Keywords: Railway switch & crossing (S&C) system, fault detection, model-based technique, condition monitoring system.

1. INTRODUCTION

Recently, many countries have adopted the philosophy of using public transportation and encouraging their citizen to not drive their private cars. The better approach to adopt this philosophy is to enhance the existing public transportation network and/or building completely new lines and routes. One of this public transportation systems is the railway. Up to the 2018 worldwide market for railway industry study [1], an increased annual growth rate of 1.1% was found between 2016 and 2018, and will continue their growth as can be seen in Fig. 1.

Good prospects are expected from this growth, however, in the meantime a high performance of the rail network should be guaranteed, especially its availability, reliability, and safety [2]. Thus, leading technologies should be adopted to the railway network system, including condition monitoring system (CMS) [3, 4], to ensure the safe and reliable running of the trains, especially with the increased use of high-speed ones on the rail network.

Nowadays, the railway network maintenance experts visit and inspect the rail regularly at fixed intervals. They base on their experience and insight to detect any abnormalities. Usually, these planned on-site inspection surveys take many days [5]—in which may cause human errors, where the experts can miss some abnormalities that can cause accidents. Especially, in the switch & crossing (S&C) systems (also known as turnouts or points) as they are one of the key infrastructure components in the railway network [6].

The railway S&C system is a safety critical asset in the rail network that is always required to be highly reliable [7]. Any failure in this system can cause delays in the rail network and/or even fatal accidents, such as the Grayrigg

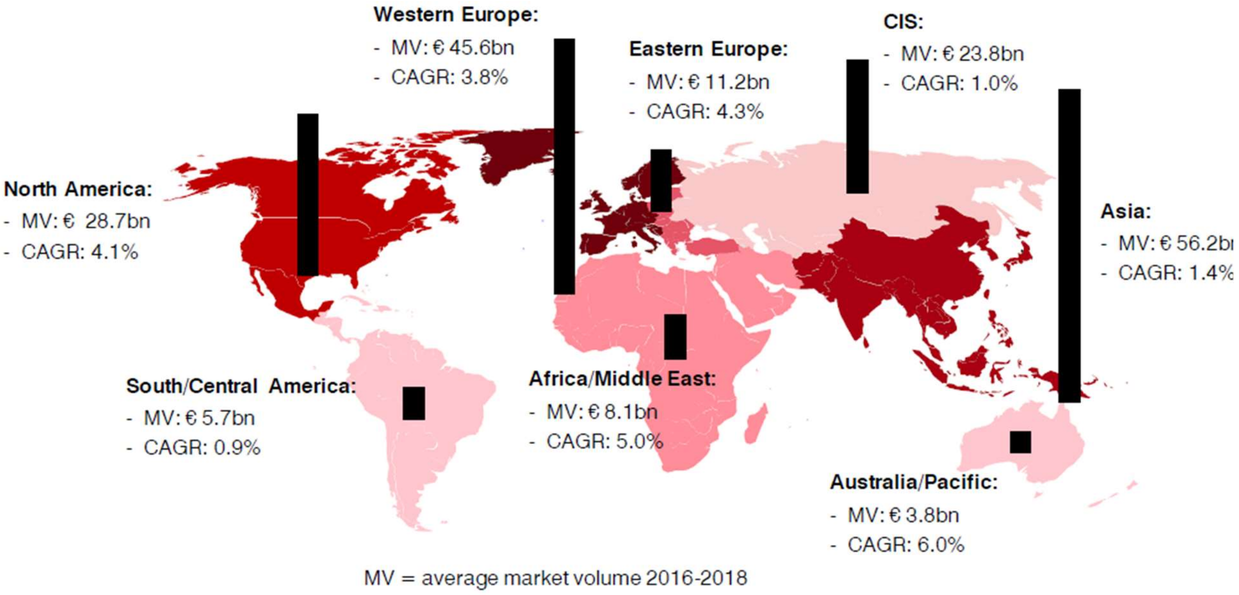

Fig. 1 Current market volume (MV) and growth rate (CAGR) by regions until 2022 [1].

accident in 2007[8]. Therefore, developing and adopting a reliable CMS for detecting, diagnosing, and prognosing the S&C system health condition is an important aspect that both researchers and railway infrastructure managers should consider. Thus, in this paper, a residual-based fault detection (FD) technique with application to a railway S&C system (i.e. electro-mechanical switch) is proposed.

In the CMS field, if an accurate enough *reference model* can be obtained, model-based fault detection and diagnosis (FDD) method can achieve accurate and timely diagnostic information [9]. No much work have been done that used a model-based FDD method to detect, diagnose, and prognose (sometimes) the health conditions of the railway S&C system. In [10], a Kalman filter (KF) with fixed interval smoothing (FIS) algorithm was used for state estimation, and combined with the maximum likelihood (ML) approach to estimate the unknown parameters of the S&C system for FD. Different wear induced faults, including dry slide chairs, lubricated slide chair, and backdrive overdriving at heel on normal and reverse side with dry and lubricated slide chairs were analyzed. The output signals were the force and DC motor current, whereas the supply voltage was considered as the input signal (it was considered constant). Another model-based FDD algorithm based on the fuzzy neural network algorithm to build the *reference model* of the railway S&C system was published in [11]. Different faults of the S&C system were considered such as switch machine idle, hard to release, etc., with acquiring only the current signal as the output signal. Their results showed that they could detect and diagnose these different faults with a good accuracy (about 96.7%). A model-based condition monitoring scheme to detect any abnormalities on the new designed REPOINT track switch was published by Wright et al. [12] and a modified Bayesian network model combined with Monte Carlo simulations for prediction of weather-related failures in the railway S&C system was developed by Wang et al. [13]. Finally, a model-based fault prognosis method for remaining useful life (RUL) prediction of S&C system health condition was proposed in [14]. It was based on an autoregressive moving average (ARMA) model. Several signals were collected (e.g., tension, force, current, voltage, etc.) to predict the RUL of the S&C system under contaminated slide chair failure mode only. More recently, an auto-associative residual (AAR) model-based approach for railway S&C system FDD was proposed in [15].

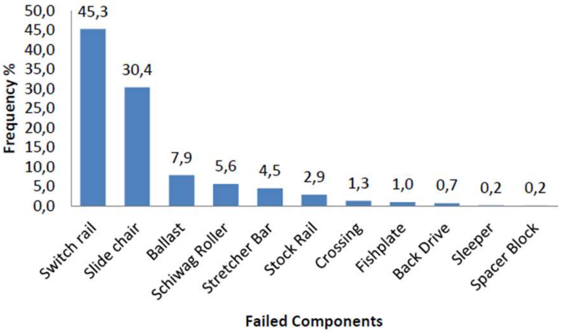

Fig. 2 The total number of failed components in 2009 [16].

As can be seen, it is clear that only few works that applied model-based FDD technique for the railway S&C system. Further, very few among these published papers that actually considered the residual-based principle for S&C system FDD. This paper thus, investigates the application of a residual-based method to detect the railway electro-mechanical switch system health conditions. Further, an assessment of several signals, including the motor speed signal, the motor stator current signal, the force signal, and the linear position of the switch rails (i.e., the switch toe position), is performed in this paper to assess the sensitivity of each of these signals to the examined fault. Whereas in this paper, only an excessive viscous friction of the switch system is considered, but under different severity levels. This choice was based on the failure analysis of the railway S&C for the purpose of preventive maintenance study performed by Hassankiadeh et. al. [16] and their results that can be seen in Fig. 2.

This paper is organized as follows: Section 2 introduces the considered railway electro-mechanical switch system and its mathematical modelling. The applied residual-based technique for FD and the simulation results are detailed in Section 3. Finally, a conclusion is given in Section 4.

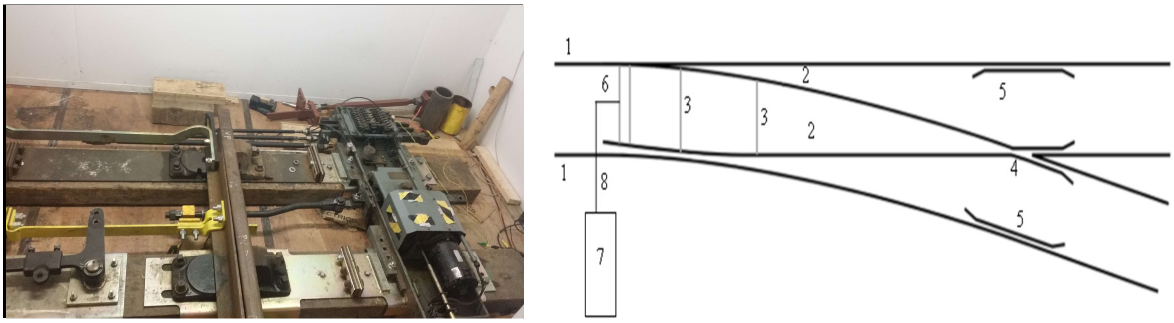

Fig. 3 The electro-mechanical switch actuating system located at the Birmingham Centre for Railway Research and Education (BCRRE), University of Birmingham (left); and the schematic diagram of a conventional switching layout (right): 1. stock rails, 2. switch rails, 3. stretcher bars, 4. common crossing, 5. check rails, 6. front-toe, 7. point operating equipment (POE), 8. actuator.

2. THE ELECTRO-MECHANICAL SWITCH SYSTEM AND ITS MATHEMATICAL MODELLING

2.1 The electro-mechanical switch system

Railway S&C system have a very complex structure that contains a large number of components as can be seen in Fig. 3. These components are mechanical devices to operate switches, electrical and/or electronics devices for controlling, etc., that include: stock rails, switch rails, stretcher bars, common crossing, check rails, front-toe, point operating equipment (POE), and an actuator. The latter is connected to the front-toe and it provides the switching motion for the switch rails (i.e., the blades). Whereas, the blades are linked through three stretcher bars.

Usually, different signals are collected. Whereas, for driving the S&C system, the input signal is the power supply voltage and the output signal is either the speed or the stator current based on the control system type. In this work, for applying the proposed model-based FD technique (i.e., the residual-based algorithm) to detect the system health conditions, several signals are considered. Whereas, the input signal is the same as the S&C input signal (i.e., the power supply voltage) and the output signal is different each time that the required residuals are generated. These output signals are the motor speed, the motor stator current, the force, or the linear position of the switch rails. The residuals are the error between the real switch system output signal and the *reference model* output signal (i.e. the estimated system output).

2.2 Mathematical modelling

The considered electro-mechanical system, shown in Fig. 3, is composed of an electrical motor-gearbox assembly, and two switch rails (blades). The gearbox is connected to the middle of the front-toe through ball-screw and mechanical linkages. The real electro-mechanical switch system, located at the Birmingham Centre for Railway Research and Education (BCRRE), University of Birmingham, and its simplified schematic diagram are shown in Fig. 4.

The electrical motor is modeled as follows:

$$V_s = I_M R_M + \dot{I}_M L_M + \dot{\theta}_M K_{emf} \tag{1}$$

$$T_M = I_M T_{Mc} \tag{2}$$

where, V_s is the power supply voltage, I_M is the motor stator current, R_M is the motor armature resistance, L_M is the motor armature inductance, $\dot{\theta}_M$ is the motor angular velocity, K_{emf} is the motor back emf constant, T_M is the motor electrical torque, and T_{Mc} is the motor torque constant.

The motor-gearbox rotational equation can be given as follows because the shaft that connect the motor and the gearbox is assumed extremely stiff.

$$(J_M + J_G)\ddot{\theta}_M + (B_M + B_G)\dot{\theta}_M + F_s = T_M + {}^{T_G}/_{\eta_G} \tag{3}$$

where, J_M is the motor inertia, J_G is the gearbox inertia, B_M is the motor friction coefficient, B_G is the gearbox friction coefficient, F_s is the static friction, T_G is the gearbox output torque, and η_G is the gear ratio. The relation between the gearbox angular velocity and the motor angular velocity is given as

$$\dot{\theta}_G = \eta_G \dot{\theta}_M \tag{4}$$

and the gearbox output torque is defined as

$$T_G = K_G\left(\theta_G - {}^{2\pi x_{BS}}/_{B_{BS}}\right) + D_G\left(\dot{\theta}_G - {}^{2\pi v_{BS}}/_{B_{BS}}\right) \tag{5}$$

where, K_G is the gearbox rotational stiffness, θ_G is the gearbox output angular position, x_{BS} is the ball-screw linear displacement, B_{BS} is the ball-screw friction coefficient, D_G is the gearbox rotational damping, and v_{BS} is the ball-screw linear velocity.

The ball-screw converts the gearbox output rotational motion to a linear motion of the front-toe according to the following equation

$$J_{BS}\ddot{\theta}_{BS} + B_{BS}\dot{\theta}_{BS} + F_s = T_G - T_{BS} \tag{6}$$

where, J_{BS} is the ball-screw inertia, θ_{BS} is the ball-screw angular position, and T_{BS} is the ball-screw load torque. Thus, the relation between the rotational velocity $\dot{\theta}_{BS}$ and the linear velocity $\dot{x}_{BS}$ of the ball-screw and its rotational displacement θ_{BS} and its linear displacement x_{BS} are defined as

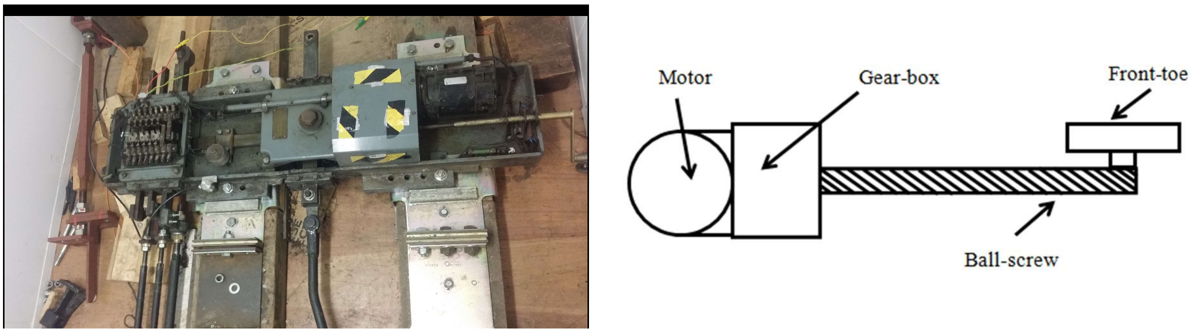

Fig. 4 The real electro-mechanical switch system (left); and its simplified schematic diagram.

$$\dot{x}_{BS} = {}^{\dot{\theta}_{BS} l_{BS}}/_{2\pi} = \dot{x}_{FT} \quad (7)$$

$$x_{BS} = {}^{\theta_{BS} l_{BS}}/_{2\pi} = x_{FT} \quad (8)$$

where, l_{BS} is the screw length, $\dot{x}_{FT}$ is the front-toe linear velocity, and x_{FT} is the front-toe linear displacement.

Using a stiff spring-damper assembly to connect the ball-screw and the front-toe will provide the same linear motion for both. Whereas, the actuator force applied to the front-toe is computed as follows.

$$F_{total} = D_{BSFT}(v_{BS} - v_{FT}) + K_{BSFT}(x_{BS} - x_{FT}) \quad (9)$$

where, D_{BSFT} is the damping of the ball-screw and front-toe assembly and K_{BSFT} is the stiffness of the ball-screw and front-toe assembly. And the load torque of the ball-screw and front-toe assembly is given by

$$T_{BSFT} = {}^{F_{total} l_{BS}}/_{2\pi} \quad (10)$$

The total system model will be defined as the relationship between the ball-screw rotational displacement θ_{BS} (i.e., its linear displacement x_{BS} which equal to the front-toe linear displacement x_{FT} as shown in Eq. (8)) and the motor stator current I_M, which it is related directly to the power supply voltage V_s. Thus, the simplified linear model of the total system can be given as

$$J_{total}\ddot{\theta}_{BS} + B_{total}\dot{\theta}_{BS} + K_{total}\theta_{BS} = T_{Mc} I_M \quad (11)$$

and the transfer function can be computed by taking the Laplacian transform of Eq. (11) and it is defined as

$$G(s) = \frac{\theta_{BS}(s)}{I_M(s)} = \frac{{}^{T_{Mc}}/_{J_{total}}}{s^2 + \left({}^{B_{total}}/_{J_{total}}\right)s + {}^{K_{total}}/_{J_{total}}} \quad (12)$$

where, the total inertia J_{total} of the switch and the motor, the equivalent spring stiffness of the rails K_{total}, and the viscous friction coefficient of the total system B_{total} are calculated as

$$J_{total} = J_M + J_G + J_{BS} \quad (13)$$

$$B_{total} = B_M + B_G + B_{BS} \quad (14)$$

$$K_{total} = K_G + K_{BSFT} \quad (15)$$

Four faulty scenarios (i.e., motor fault, total system overloaded fault, switch blade changes fault due to spring force stiffness changes, and excessive friction or resistance fault) can be considered that depend on any changes on the motor torque constant T_{Mc}, the total inertia J_{total}, the equivalent spring stiffness of the rails K_{total}, and the viscous friction coefficient of the total system B_{total}, respectively. It should be noted that in this paper, only the last fault scenario (i.e., excessive friction or resistance fault) is considered by changing only the viscous friction coefficient of the total system B_{total} that represent the friction coefficient between the sleeper and the rails as given in the Table 1.

Table 1 Friction coefficient between sleeper and the rails.

	Case 1 (healthy)	Case 2 (Fault 1)	Case 3 (Fault 2)
B_{total}	0	0.001	0.0025
	Case 4 (Fault 3)	Case 5 (Fault 4)	Case 6 (Fault 5)
B_{total}	0.005	0.01	0.02

3. RESIDUAL-BASED TECHNIQUE FOR FD OF THE RAILWAY SWITCH SYSTEM: SIMULATION RESULTS

A simulation model of the analyzed electro-mechanical switch system was developed in Matlab/Simulink as shown in Fig. 5, where the input is the power supply voltage and the outputs are the motor speed [rad/sec], the motor stator current [A], the force

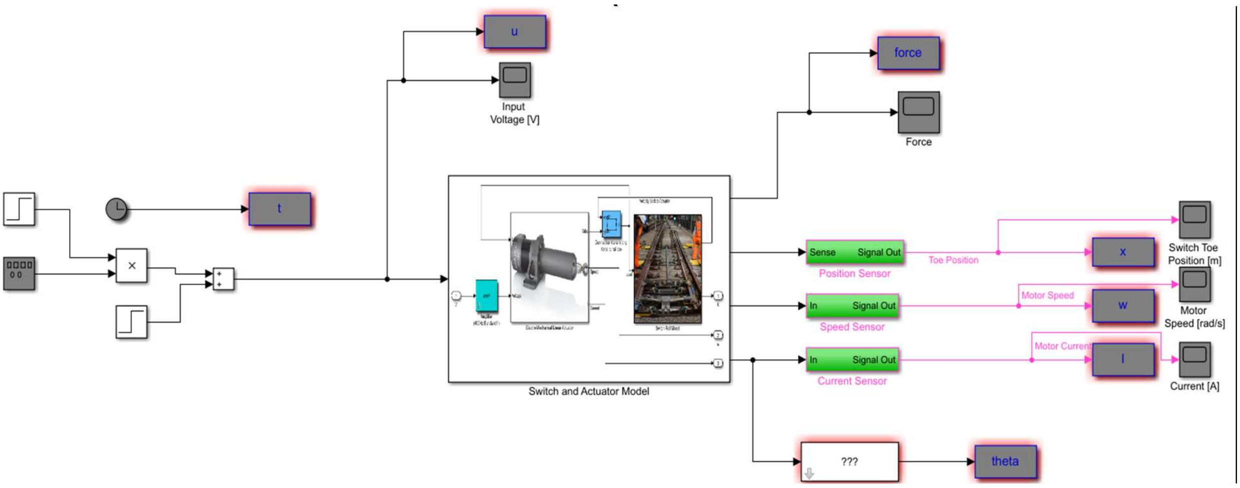

Fig. 5 Simulink block of the electro-mechanical switch system.

[N], and the linear position of the switch rails (i.e., the switch toe position) [m]. The proposed model-based FD method was conducted and tested in six scenarios, healthy case and five faulty cases as summarized in Table 1. Whereas, only a change in the friction coefficient between the sleeper and the rails was considered with different levels.

The input and the different output signals under healthy case are shown in Fig. 6.

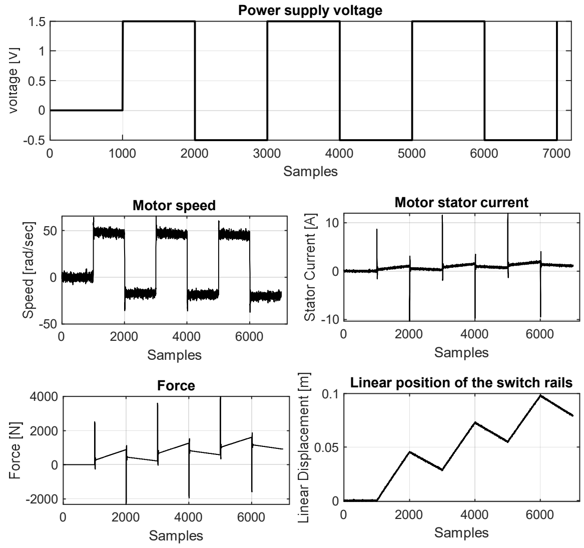

Fig. 6 The input and the different output signals under healthy condition.

Fig. 6 shows the electro-mechanical switch system dynamic response with the different output signals when was fed with a series of step voltage input.

The residuals between the real system output $y(k)$ and the *reference model* output $\hat{y}(k)$ for each output signal under the different faulty cases (i.e., from fault 1 to fault 5) are shown in Fig. 7. These residuals are computed as fellows.

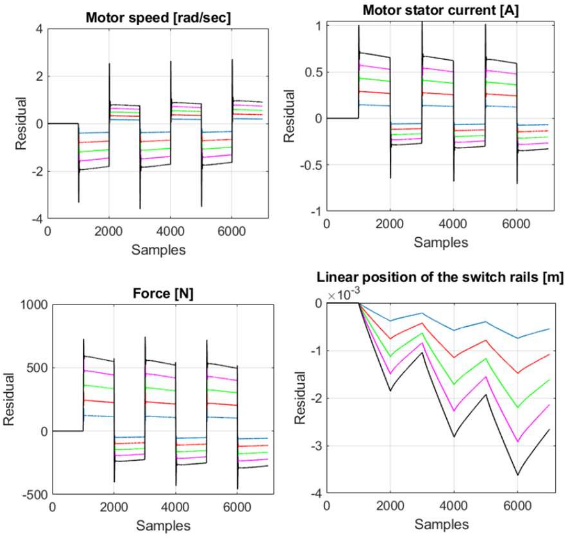

Fig. 7 Residuals under the different health conditions: fault 5 in black, fault 4 in magenta, fault 3 in green, fault 2 in red, and fault 1 in blue color.

$$r = \hat{y}(k) - y(k) \quad (16)$$

Observing the variation of these residuals, the detection of these different fault cases is possible, but with one drawback. These results may be clear for the experts in the CMS field, but probably not for the operators and technicians in the rail network, which will not recognize the presence or not of fault in the system, except when considering the linear position of the switch rails. Thus, another way to make these residuals more readable to both experts and operators/technicians is proposed in this paper.

Accumulative residual vectors r_{acc} were computed and analyzed to see how they will differ from simply and directly observing the residuals variation. The new form of the residuals proposed in this paper is simply the accumulation of the error between the real system output(s) and the reference model output(s), which is defined as follows.

$$r_{acc} = \sum_{i=1}^{N} \hat{y}(i) - y(i) \quad (17)$$

where, *N* is the samples number.
The proposed accumulative residual vectors evaluation is shown in Fig. 8.

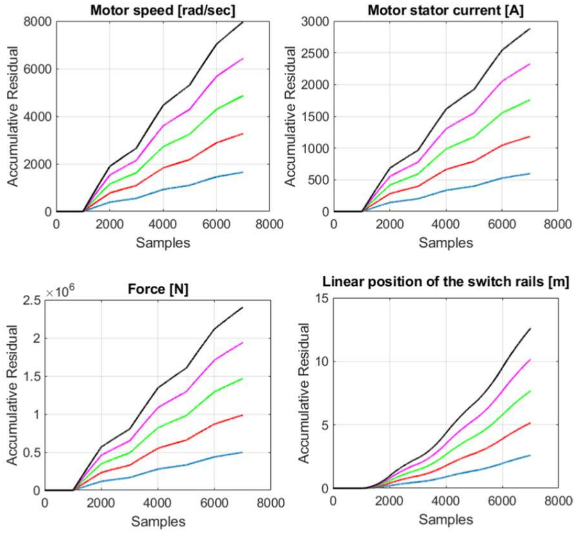

Fig. 8 Accumulative residuals under the different health conditions: fault 5 in black, fault 4 in magenta, fault 3 in green, fault 2 in red, and fault 1 in blue color.

Fig. 8 shows the proposed accumulative residuals evaluation under the different faulty cases (from fault1 to fault 5) and it is clear that these proposed accumulative residuals evaluation is more readable than of those shown in Fig. 7 when considering simply the residuals variation. Further, it is very clear that the proposed residual-based FD can detect the presence or not of the different levels of the excessive friction or resistance fault that can often appear in the railway S&C system. Thus, the proposed accumulative residuals are more suitable to be integrated in the real rail network system. It should be noted that the considered fault scenario (i.e., excessive friction or resistance fault) can be detected using all the different outputs signals, including the motor speed signal, the motor stator current signal, the force signal, and/or the linear position of the switch rails.

4. CONCLUSION

In this paper, a modified way of how to compute the residuals between the real system output(s) and the *reference model* output(s) is proposed. The modified model-based FD method did improve the readability and interpretability of the results. The proposed model-based FD method was applied to a railway S&C system. The performance and effectiveness of the proposed residual-based FD method is demonstrated using a simulation environment with a set of different fault levels. These different fault level cases were analyzed for the excessive friction or resistance fault in an electro-mechanical switch system since been one of the major faults in the railway S&C system. Further, the results show that the considered fault scenario (i.e., excessive friction or resistance fault) can be detected using all the different output signals, including the motor speed signal, the motor stator current signal, the force signal, and/or the linear position of the switch rails.

For future work, field test will be conducted on the real electro-mechanical switch system located at the BCRRE, University of Birmingham under real conditions and under other fault types, including motor fault, total system overloaded fault, and/or switch blade changes fault due to spring force stiffness changes.

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REFERENCES

[1] SCI Verkehr GmbH, *Worldwide Market For Railway Industries Study*, InnoTrans, Sep. 2018, 20 pages.

[2] M. Hamadache, J. H. Jung, J. Park, B. D Youn, "A comprehensive review of artificial intelligence-based approaches for rolling element bearing PHM: shallow and deep learning," *JMST Advances*, Vol. 1, No. 1–2, pp. 125–151, June 2019.

[3] M. Hamadache, D. Lee, E. Mucchi, and G. Dalpiaz, "Vibration-based bearing fault detection and diagnosis via image recognition technique under constant and variable speed conditions," *Applied Sciences*, Vol. 8, No. 8, 19 pages, 17 Aug. 2018.

[4] M. Hamadache, D. Lee, "Principal component analysis based signal-to-noise ratio improvement for inchoate faulty signals: Application to ball bearing fault detection," *International Journal of Control, Automation and System*, Vol. 15, No. 2, pp. 506-517, 19 January 2017.

[5] *Two Koreas to begin 16-day joint railway inspection on Friday*, Seoul says, https://www.nknews.org/2018/11/two-koreas-to-begin-16-day-joint-railway-inspection-on-friday-seoul-says/, (accessed on 15 June 2019).

[6] D. Ou, R. Xue, K. Cui, "A data-driven fault diagnosis method for railway turnouts," *Transp. Research Record*, pp. 1–10, 27 March 2019.

[7] V. Atamuradov, K. Medjaher, F. Camci, P. Dersin, N. Zerhouni, "Degradation-level assessment and online prognostics for sliding chair failure on point machines," *IFAC PapersOnLine*, Vol. 51-24, pp. 208–213, 2018.

[8] *Rail Accident Investigation Branch, Rail Accident Report: Derailment At Grayrigg*, 23 February 2007: Rail Accident Investigation Branch, Report No: 20/2008, Department for Transport, the Wharf, Stores Road, Derby, UK, DE21 4BA. 2009.

[9] S. X. Ding, "*Model-based Fault Diagnosis Techniques: Design Schemes, Algorithms, and Tools*," Advances in Ind. Control, Springer, 2008.

[10] F. P. G. Márquez, D.J.P. Tercero, F. Schmid, "Unobserved component models applied to the assessment of 939 wear in railway points: A case study," *European Journal of Operational Research*, Vol. 176, pp. 1703–1712, 2007.

[11] Y. Cheng, H. Zhao "Fault detection and diagnosis for railway switching points using fuzzy neural network," *2015 IEEE 10th Conf. on Ind. Electr. and Appl. (ICIEA)*, pp. 860–865, 15-17 June 2015.

[12] N. Wright, et al. The performance and control requirements of a REPOINT track switch," *In: Proceedings of the 2nd Inter. Conf. on Railway Tech.: Research, Development and Maintenance, Civil-Comp Press*, Stirlingshire, UK, Paper 215, 2014.

[13] G. Wang, T. Xu, T. Tang, T. Yuan, and H. Wang, "A Bayesian network model for prediction of weather-related failures in railway turnout systems," *Expert Syst. with Applications*, Vol. 69, pp. 247–256, 2017.

[14] A. Guclu, H. Yılboga, O.F. Eker, F. Camci, and I. Jennions, "Prognostics with autoregressive moving average for railway turnouts," *Annual Conf. of the Progn. and Health Manag. Society*, 6 pages, 2010.

[15] Z. Shi, Z. Liu, and J. Lee, "An auto-associative residual based approach for railway point system fault detection and diagnosis," *Measurement*, Vol. 119, pp. 246–258, 2018.

[16] S. J. Hassankiadeh et al. "*Failure analysis of railway switches and crossings for the purpose of preventive maintenance*," Master Thesis, Division of Highway and Railway Engineering, Department of Transport Science School of Architecture and the Built Environment, Royal Institute of Technology, Stockholm, Sweden, 2011.