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Health Monitoring Of a Railway Track Switch Actuator Based On Continuous-Time Parameter Estimation Method

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Abstract

The maintenance of the Railway track switches, which are exposed to environment, are very critical as any failure in the switch system may lead to accidents. With the increase of the capacity in the network, availability of switches is very important which limits the schedule maintenance process. Parameter estimation techniques can be used to estimate and detect the gradual degradation of the system. In this research, a Simplified Refined Instrumental Variable based continuous time parameter estimation method is used to monitor the condition of a railway track switch actuator. This approach will lead to reduce the number of scheduled maintenance of the switch system. In the present study, a switch system with electro-mechanical actuator, which is in operation in the UK rail network, has been modelled using the multibody model. This technique is tested with changing switch parameters and it detects changes in the system parameters such friction, stiffness elements.

Keywords: Railway Track Switch; Parameter Estimation; Continuous Time Systems; Railways; Health Monitoring.

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1.1.1. Nomenclature

B_{bs}	Ball-screw frictional coefficient
B_g	Gearhead frictional coefficient
B_M	Motor frictional coefficient
C_{fs}	Damping of the ball-screw and front-toe assembly
C_{gh}	Rotational damping of the gearhead
F_L	Load on the ball-screw
I_A	Motor current
J_{bs}	Ball-screw Inertia
J_g	Gearhead Inertia
J_M	Motor Inertia
J_t	Inertia of switch + Motor (total sys)
K_f	Viscous friction for total system
K_{fs}	Stiffness of the ball-screw and front-toe assembly
K_{gh}	Rotational Stiffnes of the gearhead
K_{spr}	Equivalent "spring stiffness" of the rails
K_T	Torque constant of the motor
K_V	Back emf constant of the motor
L_A	Armature induction
l_{bs}	Lead of the screw
n_g	Gear Ratio
R_A	Armature resistance
$Stat(T, \omega)$	Static Friction
T_{go}	Gearhead output torque
T_L	Load Torque on the ball-screw
T_M	Motor electrical torque
v_{bs}	Ball-screw linear velocity
v_{ft}	Front-toe velocity
V_M	Motor voltage
x_{bs}	Ball-screw linear displacement
x_{ft}	Front-toe displacement
θ_{bs}	Leads-screw angular position
θ_{go}	Gearhead output angular position
θ_M	Motor angular position
ω_{go}	Angular velocity of gearhead output shaft
ω_M	Motor angular velocity

2. Introduction

The railway track switches are important assets in the railway network which direct the trains to different routes. Maintenance of railway track switches is essential to ensure smooth running of the network. Corrective and preventive maintenance are the two most common strategies used in switches and a good amount of regular maintenance schedules are designed for these. However, these schedules are found to be costly and time-consuming with the advancement of high speed trains and increased train density [Márquez et al. (2008, 2010)]. A possible alternative is the predictive maintenance process, which could be able to detect the degradation in the performance and could prevent potential failure. Several researchers have studied the use of multiple redundancy, introduction of self-adjusting closed loop controller, and the use of fault-tolerant approach to monitor the condition of the switches [Bemment et al. (2018), Dutta et al. (2019), Kaijuka et al. (2018)]. Recent studies show that the predictive maintenance can be used to improve the maintenance of the switch system by inspecting and measuring some design parameters at regular inspection [COMSA (2018)].

The Instrumental variable (IV) technique to estimate a system parameter is used in many applications [Young (1985, 2006), Gilson et al. (2009), Brunot et al. (2018)]. The two main approaches of system identification are Continuous time and discrete time identification algorithms [Astrom and Eykhoff (1971), Young (1976)]. Among different techniques explained in literature, the Simplified Refined Instrumental Variable (SRIV) method of parameter estimation for continuous time systems is widely accepted in the literature [Young et al. (2006); Young (2008)] because of its advantage of a stochastic formulation of the continuous time system identification.

In the present research, a multibody co-simulation model of a working switch system has been constructed to test the health monitoring approach. A continuous time parameter estimation method is used to estimate values of the parameters of the system. Any change in the switch properties or the actuator properties are identified by the algorithm, which is presented in this study.

3. Railway Track Switch System

Fig. 1 shows the schematic of a conventional switch layout with the different elements. The actuator, which is connected to the front-toe of the switch, provide the switching motion to the switch rails. The switch rails are connected together with the help of three stretcher bars. The number of stretcher bars vary depending on the length of the switch. In the present study, a conventional C-type shallow depth vertical switch (CVS) system is considered [Network Rail (2011)].

Upon receiving command from the signaling system, the actuator (shown as number 8 in Fig. 1) drives the switch toe from one position to the other. The switch system consists of two linear position sensors at the toe which is used to measure the displacement of the actuator at the toe. The other available output of the switch system is the motor current. The parameter estimation technique developed in this research uses these two data from the switch system.

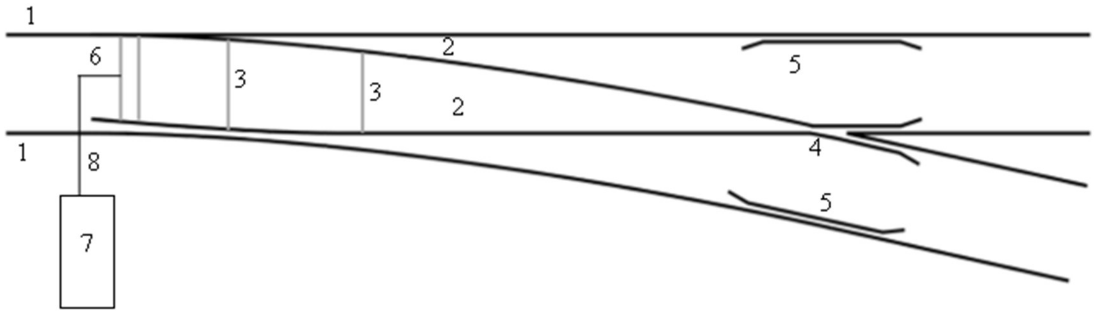

Fig. 1 Schematic diagram of a conventional switching layout: 1. Stock Rails, 2. Switch Rails, 3. Stretcher Bars, 4. Common Crossing, 5. Check Rails, 6. Front-toe, 7. Point Operating Equipment (POE), 8. Actuator.

4. Modelling of the Switch System

The mathematical model of each element is developed using first principles physics. The electro-mechanical actuator, considered in this research, includes an electrical motor and gear-box assembly which is connected to a ball-screw with a short shaft. The ball-screw is connected to the middle of the front-toe through mechanical linkages as shown in the Fig. 2.

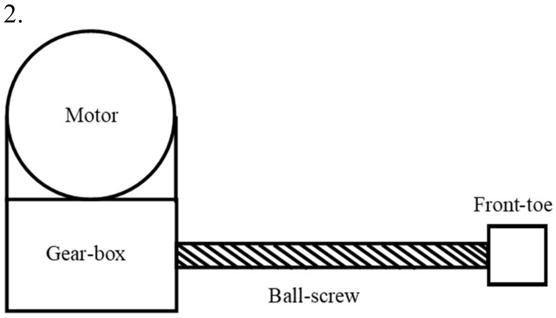

Fig. 2 Schematic diagram of the actuator

4.1. Modelling of the Actuator

The governing equations of the electrical motor are shown in equations (1) and (2). The different parameters in these equations are listed in the nomenclature.

$$V_M = I_A R_A + \dot{I}_A L_A + \omega_M K_V \tag{1}$$

$$T_M = I_A K_T \tag{2}$$

The shaft connecting the motor and the gear-box is considered to be extremely stiff, allowing the combined gear-box and motor rotational equation to be given as given as

$$\left(J_M + J_g\right)\ddot{\theta}_M + \left(B_M + B_g\right)\dot{\theta}_M + Stat(T,\omega) = T_M + T_{go}/n_g \tag{3}$$

The load torque on the gearhead is generated from the rotational stiffness between the output shaft of the gearhead and the ball-screw. The motor rotational velocity and the gearhead output velocity are related as

$$\omega_M = n_g \omega_{go} \tag{4}$$

$$T_{go} = K_{gh}\left(\theta_{go} - 2\pi x_{bs}/b_s\right) + C_{gh}\left(\dot{\theta}_{go} - 2\pi v_{bs}/b_s\right) \tag{5}$$

The ball-screw converts the rotating motion of the gearhead output shaft to linear motion at the front toe. The rotational equation of motion is written by,

$$J_{bs}\ddot{\theta}_{bs} + B_{bs}\dot{\theta}_{bs} + Stat(T,\omega) = T_{go} - T_L \tag{6}$$

The linear velocity and the rotational velocity of the ball-screw are related as,

$$\begin{aligned} v_{bs} &= \omega_{bs} l_{bs}/2\pi \\ x_{bs} &= \theta_{bs} l_{bs}/2\pi \end{aligned} \tag{7}$$

The ball-screw is considered to be connected with the front-toe in the switch panel through a stiff spring-damper assembly such that the linear motion of the ball-screw and the front-toe remains the same. The force, which the actuator exerts on the front-toe, is calculated as

$$F_L = C_{fs}\left(v_{bs} - v_{ft}\right) + K_{fs}\left(x_{bs} - x_{ft}\right) \tag{8}$$

The load torque on the ball-screw assembly is

$$T_L = F_L l_{bs}/2\pi \tag{9}$$

The output from the actuator model is the actuation force (F_L), which acts on the front-toe of the switch panel.

4.2. Co-simulation model of switch system

The switch rails are bent from one position to another when the actuation force is applied. Thus, a proper bending analysis of the switch rails are necessary. A multibody simulation model of the switch panel is created using Abaqus and Simpack following the method explained by Dutta et al. (2019). The simulation model developed is shown in Fig. 3. The switch panel model does not include the crossing as the rails do not move at that section. The rail elements assembled and shown in Simpack model are flexible bodies generated from Abaqus.

The co-simulation between the multibody simulation model and the actuator model is developed using SIMAT environment in Simulink, which is shown in Fig. 4.

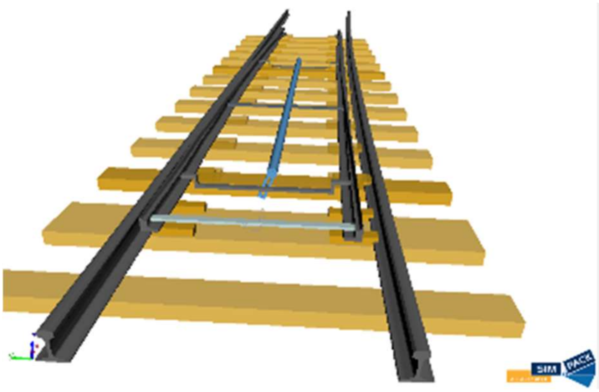

Fig. 3 Simulation model of the CVS switch panel developed in Simpack

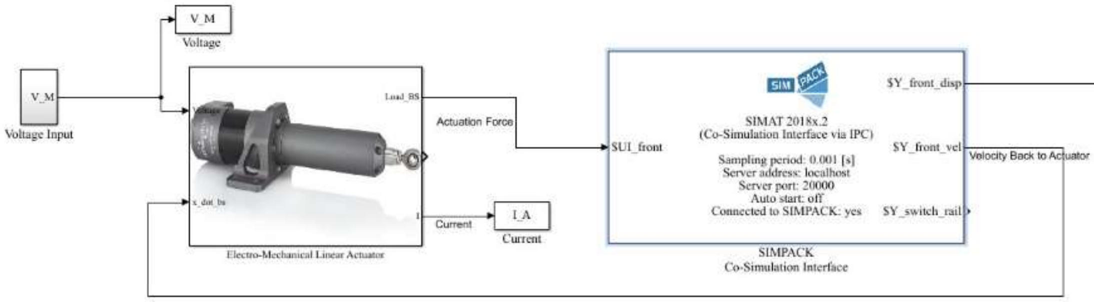

Fig. 4 Co-simulation between the switch panel (Simpack) and actuator model developed in Simulink

Fig. 5 shows the performance of the system when a pulse voltage input is fed to the actuator. The displacement at the toe, which is the output of the Simpack model, is shown in the Fig. 5. The open loop configuration of the switch system is considered in the present study.

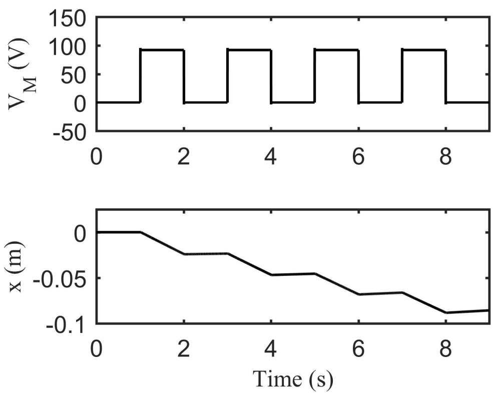

Fig. 5 Performance of the open loop system when subjected to a pulse voltage input

5. Continuous Time Parameter Estimation Method

The aim of using the continuous time identification method is to provide the provision of health monitoring of the switch system, when operates by closed loop controller. The continuous time estimation is advantageous as the parameters are not functions of sampling time, and can be directly related to the physical (meaningful) parameters of the system.

A simplified linear model of the system can be proposed as follows,

$$J_T\ddot{\theta} + K_F\dot{\theta} + K_{spr}\theta = K_T\, I \tag{10}$$

Taking the Laplace transform of Eq. 10, the transfer function can be written as

$$G(s) = \frac{\theta(s)}{I(s)} = \frac{K_T/J_T}{s^2 + s\, K_f/J_T + K_{spr}/J_T} \tag{11}$$

where,

$$\theta = \frac{x_{bs}}{l/2\pi}$$

It can be rewritten as

$$G(s) = \frac{B(s)}{A(s)} = \frac{b_0}{s^2 + s\, a_1 + a_0} \tag{12}$$

where, the coefficients are

$$b_0 = K_T/J_T\,, a_1 = K_f/J_T\,,\ and\ a_0 = K_{spr}/J_T \tag{13}$$

The four different parameters to be estimated are K_T, K_{spr}, J_T and K_f. The possible changes in the system might occur due to a change of any of the four parameters in Eq. (13). Any faults developed in the motor in the system will lead to change in K_T. The switch is subjected to harsh railway environment, thus any change in switch rails will result in change in K_{spr}. Any change in the friction elements, which is likely considering the sliding movement of the rails over the slide chairs, will result in the change in K_f. The total moment of inertia is unlikely to change unless the rotor blade mass alters. But, if the three parameters, a0, b0 and b1, all alter, then it can be concluded that this is due to the change in the value of JT. Thus, the change in four parameter can be estimated from the three estimates.

The continuous time SRIV technique of Young (1984) is implemented by the authors in MATLAB and used to calculate the parameters of a_0, a_1 and b_0.

6. Application of parameter estimation on the switch

Table 1. Change of parameters for different cases.

Test Number	Case 1 (Change of K_T)	Case 2 (Change of μ)	Case 3 (Change of K_{bs})	Case 4 (Change in J_L)
1	0.7983	0.00005	1×10^{-4}	0.8×10^{-4}
2	0.5	0.001	0.1	1×10^{-4}
3	0.6	0.0025	0.2	2×10^{-4}
4	0.7	0.005	0.3	4×10^{-4}
5	0.9	0.01	0.4	6×10^{-4}
6	1.0	0.02	0.5	7.5×10^{-4}

The parameter estimation technique is applied to the data generated from test runs from the co-simulation model in Simpack and Simulink. Four different cases are considered which changes the performance of the system. The four cases represent the changes in a single parameter at a time, torque constant of the motor (K_T), Friction coefficient between sleeper and the rails (μ), Stiffness of the ball-screw (K_{bS}) and Inertia of the system (J_L) respectively. In case 1, test number 1 corresponds to the system with normal parameter values and the other tests represents the system when the torque constant changes as given by the values in the Table 1. Six tests are carried out with changing parameters for each of the cases.

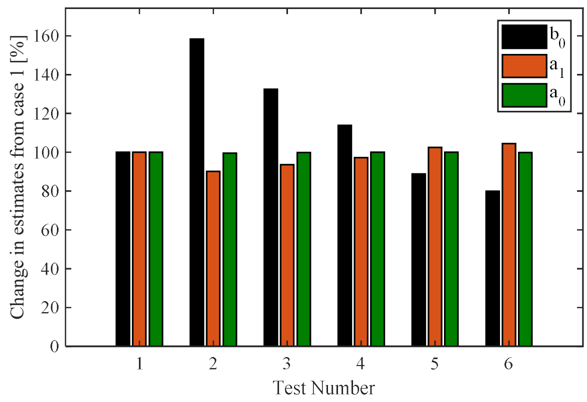

Fig. 6 Case 1: Three estimates of inertia are uncorrelated (< 0.8)

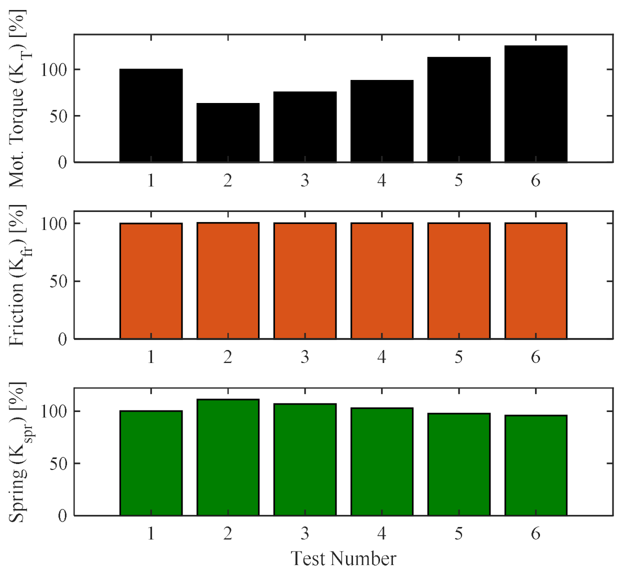

Fig. 7 Plot showing fit and co-efficient estimate Changes (as % of nominal system) over SIX tests: Case 1- changes in K_T

Fig. 6 shows the changes in the estimates of parameters when the torque constant (K_T) of the motor is changed in the simulation model. The value of torque constant K_T has been changed from 0.5 Nm/A to 1.0 Nm/A. The three bars corresponds to each test represents the coefficients b_0, a_1 and a_0 respectively, where b_0 corresponds to the change in K_T (Eq. 13). It can be seen that only the value of b_0 changes in six test runs, which is a function of K_T and inertia. But as inertia is a function of the other two coefficients as well and they did not change in these test runs, it can be concluded that the changes are in K_T only. Fig. 7 also confirms the same as it shows the fit and co-efficient estimate changes (as percentage of the nominal system) over six tests. It also shows the change in the estimate of K_T only. The small change in the value of a_1 (in Fig. 6) is not significant which is also agreed from Fig. 7.

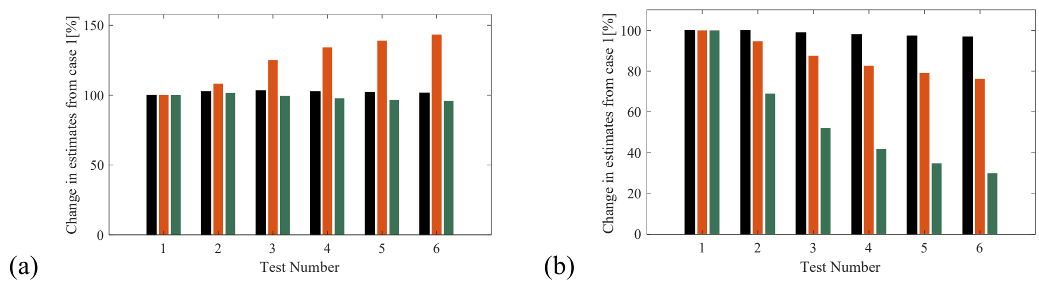

Fig. 8 Three estimates of inertia are uncorrelated (<0.8): (a) Case 2; (b) Case 3

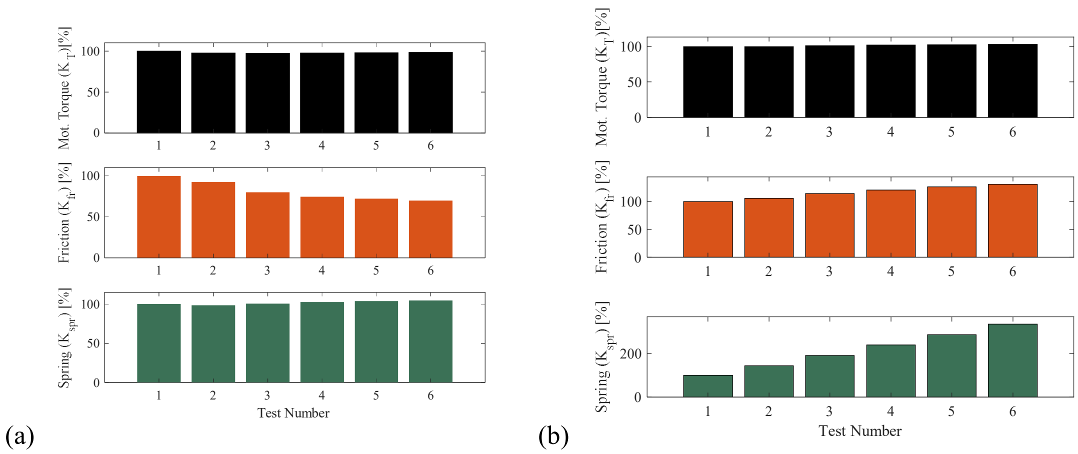

Fig. 9 Plot showing fit and co-efficient estimate Changes (as % of nominal system) over six tests: (a) Case 2, changes in μ; (b) Case 3 – changes in K_S

Similar results are reflected when the values of μ and K_S are changed in case 2 and case 3 respectively (Fig. 8). The correlation coefficients also show that the estimates of the parameters are not correlated (Fig. 9). For each of the two cases, it can be concluded that the inertia of the system did not change as the three coefficients are uncorrelated.

The total inertia of the motor is considered to vary for case 4 (as shown in Table 1), which is unlikely, but can be caused due to any defect in rotors. The result for case 4 is shown in Fig. 10. It can be seen that the estimates of three parameters changed for the test runs. From Eq. 13, it can be concluded that the three coefficients have changed due to change in inertia. The correlation coefficient from the estimates also show that these are correlated in Fig. 11.

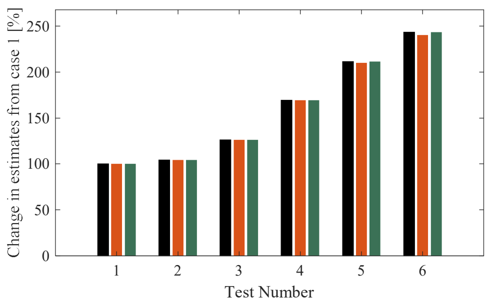

Fig. 10 Case 4: All three inertia estimates (b_0, a_1 and a_0) are correlated

7. Conclusion

The research has highlighted the use of SRIV based parameter estimation technique which can be used in monitoring health of an electro-mechanical actuator used in railway track switches. The railway track switches are required to be maintained to ensure the security and smooth running of the network. A continuous time parameter estimation can locate any degradation in parameters and the knowledge can be used in monitoring health of the actuator. The parameter estimation technique is used on a multi-body co-simulation model of a track switch. Different tests have been carried out to check the performance of the estimation technique when the parameters are varied. In the future, it is intended that the technique used in this study will be used with sensor data collected from a working track switch system.

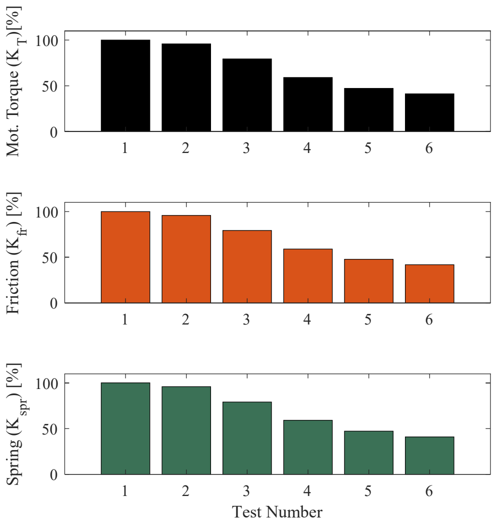

Fig. 11 Plot showing fit and co-efficient estimate Changes (as % of nominal system) over six tests when inertia changes: Case 4

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