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Modelling and Controller Design for Self-adjusting Railway Track Switch System

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Abstract

Rail vehicles are directed along different routes through track switch systems. These switches are subjected to high loads and vibrations which may introduce misalignment in the switch layout. The objective of the current project is to develop a simulation model of a 'self-adjusting' switch. The switch should be able to detect the existence of any misalignment (within a predefined range) between the stock rails and switch rails and will be able to re-align itself. The first phase of the project is to model a working track switch system, High Performance Switch System (HPSS), which is in operation in the UK. The multi-body simulation software Simpack is used to model the switch panel and Simulink is used for modelling the actuator mechanism of HPSS. A co-simulation environment is created in Simulink to construct the complete model of the switch system. The model has been validated with the data available from the working switches. The second phase of the project will be to create misalignment in the switch layout and develop a control strategy which will be able to adjust the misalignment.

Keywords: Track Switch; self-adjusting; multi-body simulation; co-simulation.

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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
K_{fs}	Stiffness of the ball-screw and front-toe assembly
K_{GH}	Rotational stiffness of the gearhead
K_V	Back emf constant of the motor
l	Lead of the ball-screw
L_A	Armature inductance
n_g	Gearhead ratio
R_A	Armature resistance
T_{go}	Gearhead output torque
T_M	Torque constant of the motor
T_L	Load Torque on the ball-screw
v_{bs}	Ball-screw linear velocity
v_{ft}	Front toe velocity
V_M	Voltage to motor
x_{bs}	Ball-screw linear displacement
x_{ft}	Front toe displacement
θ_{bs}	Ball-screw angular displacement
θ_{go}	Gearhead output angular position
θ_M	Motor-shaft angular position
ω_{bs}	Ball-screw angular velocity
ω_{go}	Gearhead output velocity
ω_M	Motor-shaft angular velocity

1. Introduction

Railway switches are the mechanisms that allow rail vehicles to transfer between different routes. A track switch is made up of a combination of moving and stationary parts. Two moving rails that guide wheelsets towards their desired direction, are called switch rails. The stationary rails are called the stock rails. Major faults and failures in track switches can lead to derailment of rolling stock, collisions between vehicles, and consequential injury or death to occupants. Switches experience high dynamic loads when vehicles pass over them, the accumulative effects of which can cause serious misalignment of the rails leading increased risk of derailment.

The switch rails are aligned depending on the requirements of the route with a wide range of switch mechanisms being used in the railway networks around the world. A variety of novel track switch methodologies are emerging from railway research organisation [Cope (1993), Bemment et al. (2013), Sarmiento-Carnevali et al. (2017)] that aim to remedy the fundamental issues with currently applied technology. A common component of the actuation mechanism that provides a maintenance burden is the stretcher bar that connects two switch rails and maintains the distance between them. This distance is set manually and failure of this item can have serious consequences like Grayrigg accident [RAIB (2011)]. The stretcher bar/switch rail combination is actuated by a lateral force applied to the switch rail by either mechanical, electrical or hydraulic actuation, with additional mechanical linkages transferring load on long switch blades. For most of the traditional switch systems the motor is powered till the switch rails reach the desired position and then the motor is turned off. The position of the switch rails and stock rails are measured in some switch systems, but this data is not used for controlling the movement of the switch rails (i.e. in the traditional sense of a 'closed loop'). Most of the research in the railway

industry is being conducted on condition monitoring of these switches. The main objectives of these studies are to reduce the major critical failure modes by condition monitoring based maintenance (i.e. detecting gradual failures before these become critical) or studying the reliability of the switches [Marquez et al. (2010), Simon and Andrews (2010), Rama and Roberts (2013)]. The option for closed loop feedback control of the switch rails has not been explored to any great deal in the current literature. Hence, the conjecture here is that the inclusion of a feedback controller in the system can improve the performance of the system by not relying on simplistic methodologies that are no longer used in the majority of industries.

The work described herein is a part of the European Commission (EC) funded IN2Rail project [In2Rail] and the specific objective of this subcomponent of the overall project is to develop a simulation model of a self-adjusting switch. A 'self-adjusting' switch should be able to detect any occurrence of misalignment (within a predefined range) between the stock rails and the switch rails or in the sleepers, and the controller should be able to re-align itself based on this information. In the present project a Network Rail (the UK rail network fixed asset operator) approved standard switch, High Performance Switch System (HPSS), is considered for investigation. This is due to the HPSS being an example of an updated and improved switch mechanism that has sensing in built that can be used for both closed loop control and condition monitoring.

In this paper, the mechanism of HPSS and its differences with conventional switch system are explained in section 2. The model of HPSS is prepared using two commercially available software packages, Simpack [Simpack, 9.10.2] and Simulink [Simulink, 16a]. The details of the modelling approach of HPSS in Simulink and Simpack is presented in section 3 and 4 respectively. Co-simulation is carried out between Simulink and Simpack models using SIMAT interface in Simulink environment, which is explained in section 5, to construct the full model of the switch. In section 6, the validation results of the simulated model with the data from a working HPSS are presented. In the next phase of the project, a controller using the feedback of the switch rail positions will be developed.

2. High Performance Switch System (HPSS) mechanism

The High Performance Switch System (HPSS) is in use on the UK rail network. A schematic diagram of the comparison between a traditional switch panel and HPSS panel is shown in Fig. 1. Conventional switches are driven by driver bars and the stretcher bars connect the two switch rails. The switch rails are locked when moved from one position to the other by an active locking mechanism. There are many alternative mechanisms for switching, but most of the switches in railways follow the same basic actuation mechanism of sliding from normal position to reverse position or vice versa. Some switch systems use a secondary drive system which ensures the minimum flange clearance in switch layout and appropriate bending of the switch if the track panel is of a long variety. The conventional switch system shown in Fig. 1 does not have any additional back drive.

The HPSS switch panel consists of three stretcher bars which connect the two switch rails. The actuation force acts on the front toe, which is connected to the switch rails. A torque tube links the front and the rear stretcher bars ensuring desired clearance of the switch rail at the rear position.

The HPSS actuator mechanism consists of an electrical motor, gearbox and a ball-screw mechanism. The ball-screw is connected to the front-toe of the switch panel. As the motor rotates, the ball-screw rotates and the front-toe moves in synchronisation.

The HPSS switch modelling has been done in two parts. The actuator mechanism is modelled in Simulink and the switch panel is modelled in Simpack. The detailed modelling approaches are described in the following section.

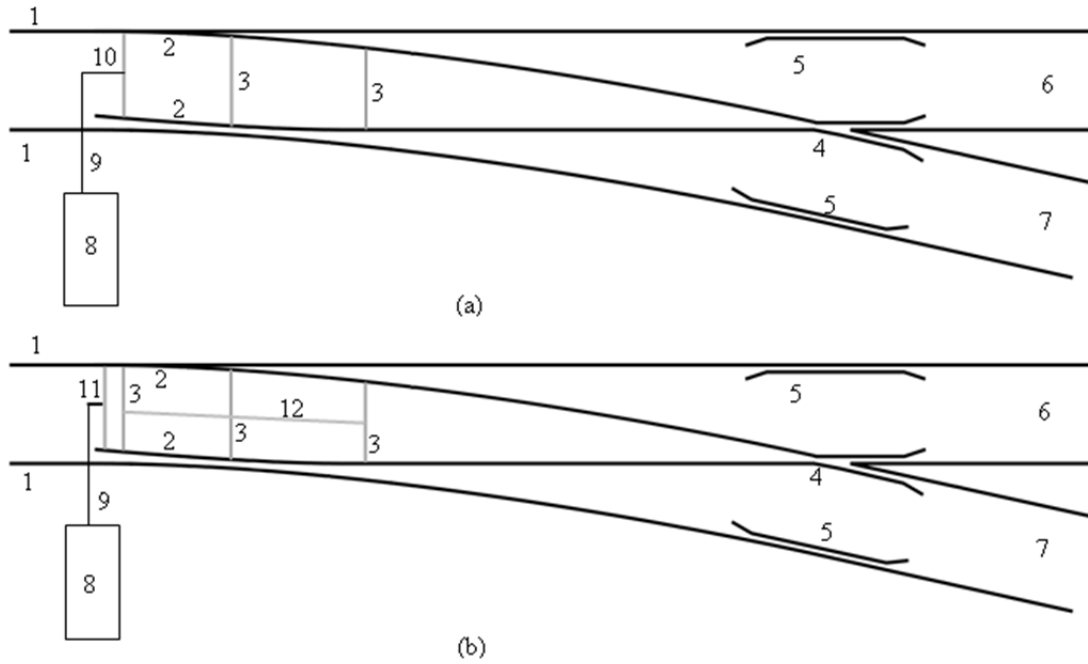


Fig. 1 Schematic of the switch system: (a) Traditional switch; (b) HPSS switch. 1 Stock Rails; 2 Switch Rails; 3 Stretcher Bars; 4 Common Crossing; 5 Check Rails; 6 Straight Route; 7 Turnout Route; 8 POE (Points Operating Equipment); 9 Actuator; 10 Drive Bar; 11 Front-toe; 12 Torque Tube

3. Modelling of the HPSS actuator

The different components of the actuator, which is shown in Fig. 2, are modelled in Simulink. The input to the actuator model in Simulink is the displacement and velocity of the front toe which is obtained from the Simpack model. The output from the actuator is the force to the switch-toe from the ball-screw. The different mechanical elements are derived from the governing equations which are described in the following sections.

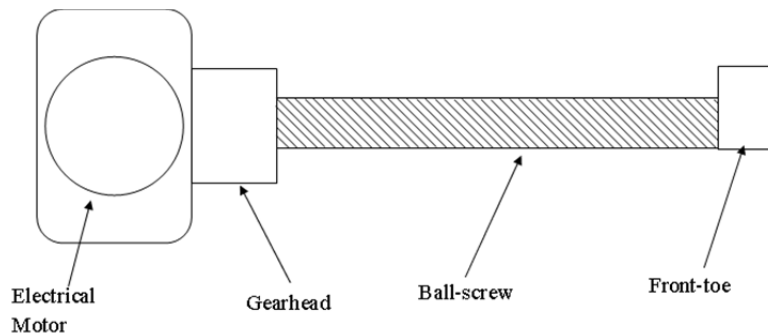


Fig. 2 Schematic of the HPSS actuator

3.1. Electrical motor and gearbox

The first part of this section is to model the electrical motor. The output shaft from the motor is connected to the gearhead. The governing equation of the motor is shown in equation 1.

$$V_M = I_A R_A + L_A \frac{dI_A}{dt} + K_V \frac{d\omega_M}{dt} \quad (1)$$

The different symbols are explained in the Nomenclature section. The motor electrical torque can be calculated as,

$$T_M = I_A K_T \quad (2)$$

The motor-shaft is attached to the gearhead input and the output from the gearhead is connected to the ball-screw. The shaft is very short and the effect of the shaft is neglected in the modelling process. As the effect of the shaft is neglected, the motor and gearhead are modelled as lumped masses and the governing equation of the lumped system is written as

$$(J_M + J_G) \ddot{\theta}_M + (B_M + B_G) \dot{\theta}_M = T_M - T_{go} / n_g \quad (3)$$

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

$$T_{go} = C_{GH} (\omega_{go} - 2\pi v_s / l) + K_{GH} (\theta_{go} - 2\pi x_s / l) \quad (4)$$

3.2. Ball-screw model

The ball-screw is driven by the gearhead and it drives the front toe of the switch panel. The governing equation for the ball-screw assembly is as follows,

$$J_{bs} \ddot{\theta}_{bs} + B_{bs} \dot{\theta}_{bs} = T_{go} - T_L \quad (5)$$

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

$$v_{bs} = \omega_{bs} \frac{l}{2\pi} \quad (6)$$

$$x_{bs} = \theta_{bs} \frac{l}{2\pi} \quad (7)$$

The force on the ball screw assembly arises from the stiffness between the ball-screw and front toe assembly. It is considered as a stiff spring-damper assembly, which does not allow relative movement between these two. The force, which the actuator exerts on the front-toe, is calculated as

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

The load torque on the ball-screw assembly is

$$T_L = F_L \frac{l}{2\pi} \quad (9)$$

The output from the actuator model is the force, which acts on the front-toe of the switch panel modelled in Simpack. The inputs to this actuator model in Simulink are the displacement and velocity of the front-toe.

4. Modelling of a switch panel

A HPSS switch panel consists of stock rails, switch rails, stretcher bars, a torque tube, front toe and sleepers. Multi-body simulation software, Simpack is used to model the full HPSS panel. Deflection in the components namely, stretcher bars, torque tube, front toe and sleepers are neglected in the modelling, with the rail bending considered by modelling these as flexible bodies.

Finite element analysis (FEA) has been carried out first to model the bending of the rails. Fig. 3 shows the finite

element (FE) visualization of a curved switch rail, which is prepared in the FEA software package Abaqus [Abaqus CAE 2016]. This analysis is based on the CVS switch layout which is in operation on the UK rail network. A rail CAD model is first imported to the Abaqus CAE software with rail bodies considered as isotropic material (steel) with Young's modulus of 200 GPa and Poisson's ratio of 0.3. The finite element mesh is created using a C3D10 element type in Abaqus CAE which is a second order quadratic tetrahedral.

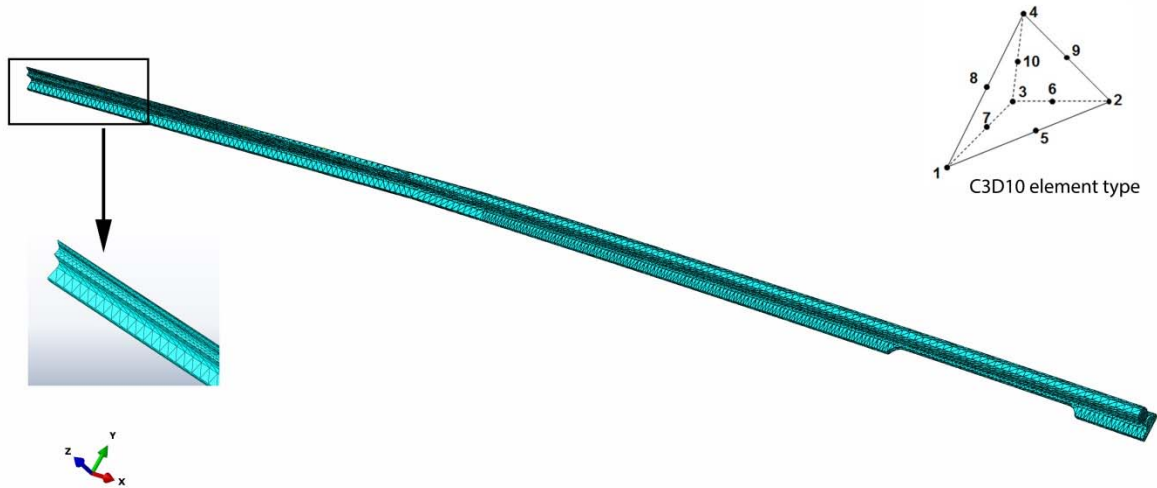


Fig. 3 Finite Element body of the switch rail modelled in Abaqus and the element type C3D10

The boundary conditions on the switch rails are used such that these restrict any motion at the heel of the switch rails. The stock rails are fixed at both ends. The natural frequency analysis is performed using 'Lanczos' eigensolver in Abaqus and the first 30 bending modes are considered to create the flexible bodies in Simpack.

These FE bodies are then converted to flexible bodies using Simpack [Simpack, 9.10.2], which is compatible with the FE elements created in Abaqus. The points of contacts of the rail section are calculated from the switch layout drawing, e.g. the contact point of the switch toe with the switch rails. The nodes around those points in the FE body are used to create surfaces at that position in the Simpack flexible body application. Following this the Simpack flexible bodies (.fbi) are created. The four rail flexible bodies, straight and curved switch rails and stock rails are generated in Simpack and the full multi-body model of the HPSS is developed which is shown in Fig. 4.

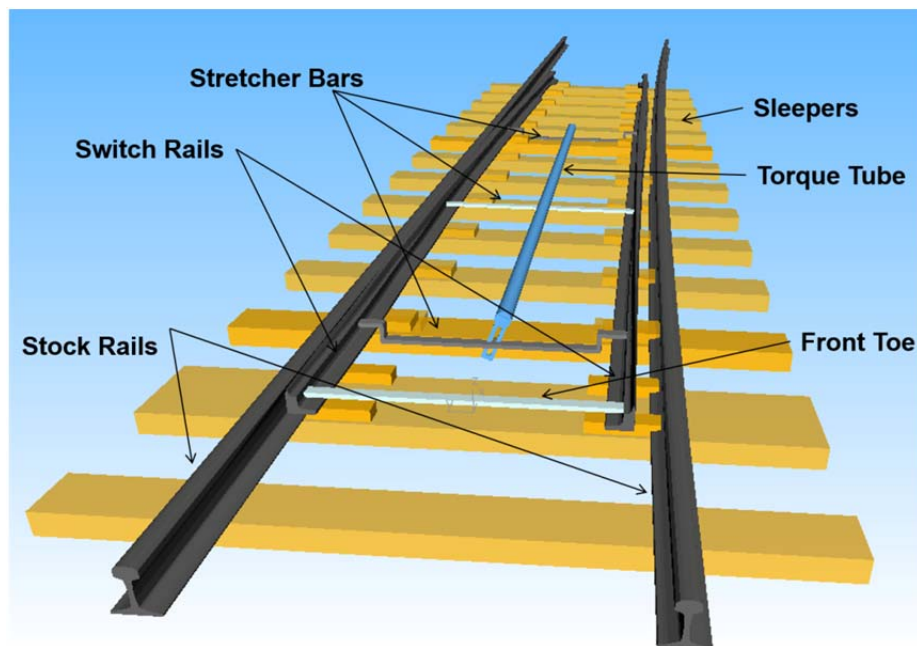


Fig. 4 Model of the HPSS switch panel in Simpack

The other elements of the switch panel, i.e., the stretcher bars, front toe, sleepers are created in Simpack as rigid bodies. The stretcher bars and the front toe are connected to the switch rails at both ends and any motion between these bodies is constrained. The torque tube is connected to the front stretcher bar and rear stretcher bar with a slotted connector. The force elements are created next. The contact forces in the connectors of the torque tube and the friction between the switch rails and the sleepers during the movement are incorporated using friction elements, which act only when the two bodies are in contact. Two contact force elements are created for potential contact between stock rail and corresponding switch rails, which will act only if the two bodies are in contact. The actuation force element is connected to the middle of the front-toe.

5. Co-simulation between Simulink and Simpack

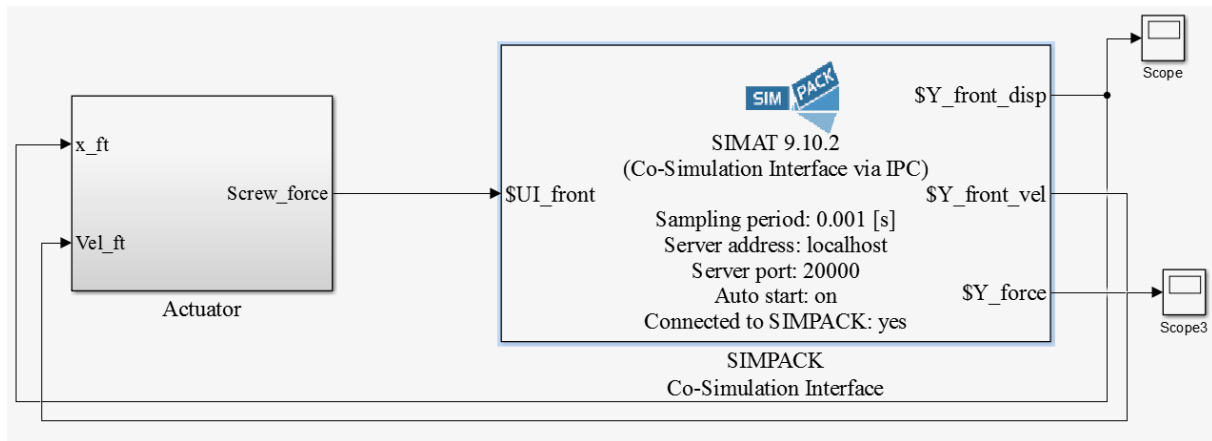


Fig. 5 Model of the HPSS switch panel in Simpack

The full model of HPSS switch is a co-simulation between Simulink and Simpack using the SIMAT interface in Simulink environment to construct the complete model of the switch, which is shown in Fig. 5. The actuator model in Simulink, which is explained in section 3, requires the displacement and velocity of the front-toe inputs from the Simpack (shown as ' x_{ft} ' and ' Vel_{ft} ' in Fig. 5) and simulates the actuation force which acts on the front-toe of the switch panel model in Simpack (shown as ' $Screw_{force}$ ' in Fig. 5). Similarly, the switch panel model in Simpack, which is explained in section 4, gets the input of the actuation force from the Simulink model (shown as ' UI_{front} ') and simulates the displacement and velocity of the front toe (shown as ' Y_{front_disp} ' and ' Y_{front_vel} ' respectively).

The switch model, which is developed, is an open-loop system. The only control is in the motor voltage. The motor is switched on for the period of travel and is switched off when the switch rail is within a predefined range.

6. Validation of the Model and Discussion

The HPSS runs as an open-loop control system. Once the signal is verified, the motor is driven to move the switch rails. The motor is stopped when the switch rail reaches a predefined range. The same process is followed in the present co-simulation.

The simulation results are validated against the available motor current data from a working HPSS switch. In Fig. 6, the simulation result is plotted against the HPSS current data. The difference in the initial peak of the current of the simulated data is due to the small time-steps used in the simulation. The differences in the modelling data and test data have caused due to difference in some parameters of the switch rail like the friction coefficient between the rails and sleeper, frictional coefficients and other parameter, which are difficult to measure.

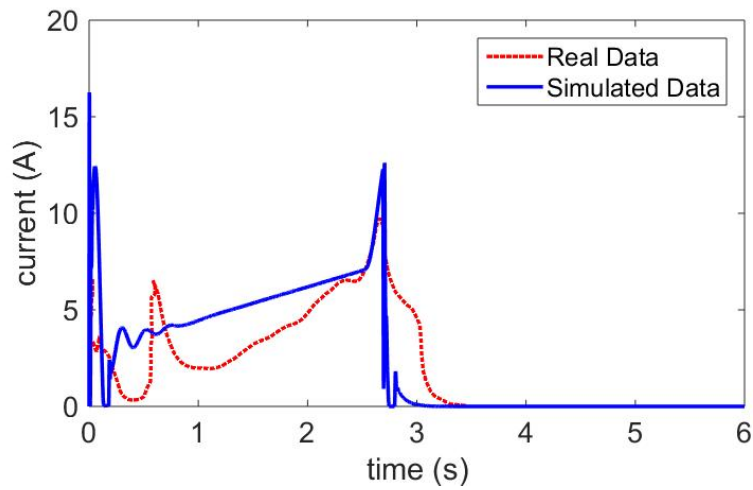


Fig. 6 Validation data of the motor current

An LVDT is connected at the middle of the front-toe of the HPSS. Fig. 7 shows the displacement of the middle point of the switch toe. In order to inspect misalignment, it is essential to measure the gap between the switch rail and the stock rail. In The switch rail travel relative to the stock rail is shown in Fig. 8. The switch rail slides from open position (at time 0.001s) to the closed position when the gap between the switch rail and the stock rail is zero.

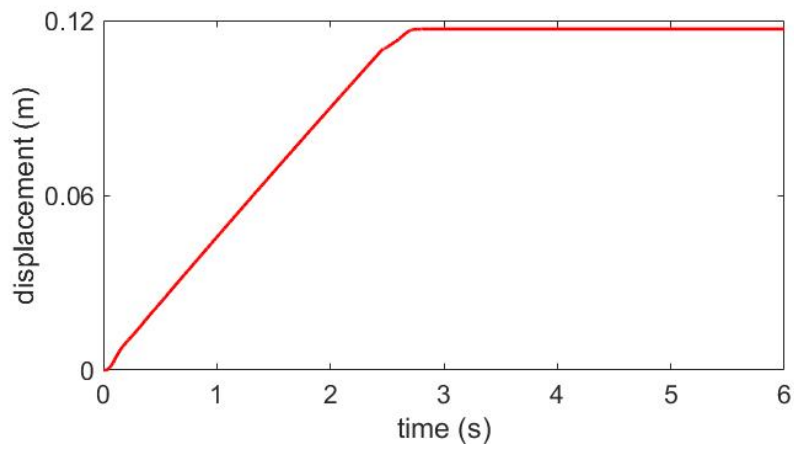


Fig. 7 Displacement of the front toe

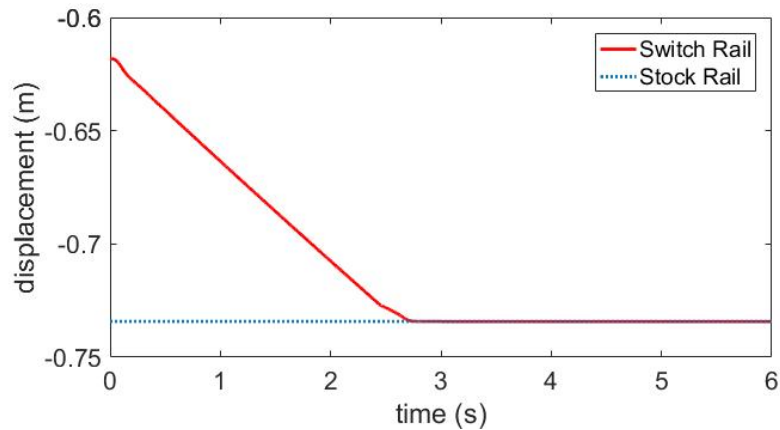


Fig. 8 Switch rail travel

There are reasons for the differences between the simulated data and the working HPSS data. The parameters like friction coefficient between the rails and sleeper, friction between the torque tube and the stretcher bar connector, friction of the ball-screw are unknown. Thus, these values are considered from engineering experiences. To run the co-simulation, the software is needed to work with very small time-steps, which is responsible for the large peak in the initial period of the simulation.

The gap of the switch rails with the stock rails can be used to design a control algorithm for the electrical motor and to determine misalignment if present in the system. The next phase of the project is to design a controller using the validated model.

7. Conclusions

The paper presents the modelling approach of a railway track switch system. The modelling involves two software packages to model the bending of the rails and the actuator mechanism. A co-simulation environment between Simulink and Simpack is explained in the current paper. The results from the modelling are validated against the real data, which is available from the working switches. In the next step of the research, a control algorithm will be developed using position feedback from the sensors attached to the switch panel. The controller will be able to locate misalignment (if any) present in the switch system and will control the motion of the switch rails accordingly to provide safe running of the trains over these. In the current configuration, the actuator does not have any control over the motion of the switch rails, whereas the new controller will be able to locate the misalignment and adjust the switch accordingly within a predefined range. The modelling work presented in this study is the first stage to develop full self-adjusting track switch system.

Acknowledgements

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