Computer modelling and simulation of jointless audio-frequency track circuits

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Abstract

This paper describes the development of a computer-aided engineering tool for the simulation of audio-frequency jointless track circuits under various operating conditions. The simulator includes track circuit physical and functional models, a mathematical formulation, a computer implementation and a validation procedure. Application of the model is demonstrated by simulation results using a practical audio-frequency jointless track circuit.

Introduction

Despite the ascendancy of transmission-based signalling systems with alternative methods of train detection and track - train data transmission, track circuits are likely to remain the principal method of train detection for urban and high-speed railways for a considerable time. Track circuits are undergoing continuous improvement and development to optimise their performance, and ensure their continued safe operation in an increasingly hostile traction environment. To achieve this in a cost-effective way, designers require versatile tools which they can use with confidence. This paper describes the design of an audio-frequency jointless track circuit simulator which has been used to verify a practical track circuit, the design of which was originally achieved in an ad-hoc manner.

Although the principle of operation of track circuits is simple, their design is not straightforward. This is because:

- Track circuits do not have a fixed operating point but must maintain fail-safe operation over a wide range of dynamically varying operating conditions.
- Track circuits are open systems and their performance is susceptible to changing external environmental factors.
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- Track circuit performance depends on a number of design parameters which may be mutually related.

Consequently, track circuit design is achieved by an iterative process of searching through a multidimensional space, defined by constraints on design parameters, for a set of actual parameters which will ensure the specified track circuit performance. This process involves evaluation of track circuit performance for specific values of the design parameters, operating conditions and environmental factors. This task is difficult if optimisation of a specific design or operational parameter is required. The availability of a CAE tool for quick and realistic evaluation of track circuit performance is thus of considerable significance.

The literature contains many references to track circuit modelling and simulation, including recent audio frequency jointless track circuits. Some simulation tools are based on professional electric circuit simulation packages [1,2,3], whilst others report the use of specially-designed computer models. This paper outlines the development of a dedicated CAE tool for track circuit simulation. Despite the necessary investment in time and programming effort this has entailed, this approach allows the user freedom to create a unique model for each application.

Model specification

An efficient purpose-built model must commence with a comprehensive statement of the required features, facilities and performance criteria. A track circuit model must meet the following requirements:

- It must represent a precise and realistic description of the physical processes occurring in track circuits, and there should be an optimum balance between detail and approximation to achieve the necessary modelling accuracy without undue increase in complexity.
- It must simulate track circuit operation under the full range of design parameter variations (including the effect of tolerances) and environmental conditions and account for both steady state and dynamically changing conditions.
- It must lead to the determination of a set of conditions resulting in best, worst or critical track circuit performance.
- It must provide user-defined output for track circuit operational variables and performance criteria.
- It must be structured, for example with provision for interface to adjacent track circuits on the same or on parallel tracks.
- It must be applicable to different types of track circuits with the minimum amount of modification and adjustment.
Modelling strategy

Fig.1 gives an overview of the model. The feedback/feedthrough modelling process includes the following four stages:

Physical and functional modelling
This establishes the essential features of the track circuit which must be reproduced by the model, and concludes with the identification of a preliminary qualitative track circuit model. The analysis is carried out in two parallel independent streams to establish the nature of the track circuit as a physical system and the particular function which it performs.

Mathematical analysis
In this stage, the preliminary physical and functional models are subjected to further analysis to determine their rigorous mathematical descriptions. In the preliminary physical model, knowledge of track circuit parameters & behaviour and electric circuit theory are required to establish the process variables and laws. In addition, the track circuit function is given a formal representation in terms of the logical relationship between the input effects and the output response.

![Figure 1: Track circuit modelling process](image)

Synthesis and solution of track circuit mathematical model
The above two streams of analysis are mutually related to yield an integral track circuit mathematical model. This is achieved by establishing the physical meaning of the input effects and output response and the physical mechanism resulting in the track circuit logical function. After the physical variables have been identified, the solution can be obtained using appropriate mathematical methods.
Computer implementation

This stage involves development of computer programs for solving the track circuit model together with test and validation. The procedure is oriented towards the model application and includes a definition of the conditions and simulation objectives in addition to the input data and the output results.

Each stage of the above modelling process interacts with the specification to ensure correct interpretation and implementation. Validation of the model is monitored at every stage of development.

Track circuit functional model

The purpose of a track circuit is to provide continuous train detection information that is unambiguously associated with a given section of rail track. At any moment and over the whole range of operating conditions the track circuit generates one of two possible pieces of information according to the following algorithm: Vital 'Section clear' information is generated if and only if the train detection section is free of vehicles and the track circuit equipment is in good working order. Otherwise, non-vital 'Section occupied' information is generated.

The above algorithm can be formally described as follows:

\[ F \left\{ x \in X_0, y \in Y, d \in D_0 \pm \Delta D \right\} = 1 \] (safety critical output)

\[ F \left\{ x \in (X \cap X_0), y \in Y, d \in D_0 \pm \Delta D \right\} = 0 \] (non-safety critical output),

where \( F \) is track circuit output response,

\( d = \{ d_1, d_2, \ldots, d_k \} \) is the set of track circuit design parameters (e.g. track circuit transmitter and receiver impedances, track circuit length, operating frequency, electrical separating joint parameters, connecting cable lengths, etc.),

\( x = \{ x_1, x_2, \ldots, x_l \} \) is the set of factors describing the operating conditions (train shunt or broken rail position, position of second train shunt on an adjacent track circuit, train shunt resistance, etc.),

\( y = \{ y_1, y_2, \ldots, y_m \} \) is the set of external factors describing the environmental conditions (e.g. rail track parameters, rail track asymmetry, crosstalk or feedthrough interference from other track circuits, EMI interference from the traction system, etc.),

\( D_0 \) is the area of existence of a track circuit, defined by the constraints on track circuit parameters,

\( X \) and \( Y \) are the definition areas of \( x \) and \( y \) and cover the whole range of operating and environmental conditions which are likely to occur, and

\( X_0 \) is a subset of \( X \), which corresponds to the safe, non-occupied track circuit condition.
Track circuit physical model

From the physical point of view, a track circuit represents a transmission network using a section of rail track as the transmission path between the track circuit transmitter and receiver. The principle of operation is based on the ability of rail track to 'sense' train shunts and rail breaks and to respond by changing its transfer properties (e.g. transfer impedance) which are then recorded by the de-energisation of the track circuit receiver. Thus in track circuit modelling it is extremely important to establish a realistic model of rail track. Here, the criteria for a realistic model can be expressed by the following two requirements:

- The rail track model should be sufficiently accurate, i.e. inaccuracies in the rail track transfer impedance due to inaccuracies of the model parameters should be much smaller than changes which occur as a response to the input effect (changes in the operating and environmental conditions).
- The model and its mathematical formulation should incorporate interactions between rail track and the input effects (train shunts or rail breaks).

These requirements can be met by modelling the rail track (with no electrification) as a two-conductor transmission line above a conductive earth plane, whereby train shunts and broken rails can be incorporated as discontinuities. This model has the following advantages:

- It provides an accurate description of the physical phenomena during track circuit operation provided the distributed electrical parameters of rail track are accurately defined.
- It is readily expandable to a multiconductor transmission line above an imperfect dielectric to cover more complex configurations such as electrified railway lines, parallel rail tracks or other conductors running in parallel to the track, the main difficulty being again the definition of the distributed electrical parameters of the multiconductor line.
- The model has a straightforward mathematical solution based on the theory of natural modes. In the case of multiconductor transmission lines, this involves complex matrix computation; however, numerical methods for their solution are available and supported in most libraries of mathematical subroutines.

Transmitter and receiver track circuit terminations are modelled as lumped parameter networks. To achieve more concise models, however, they are represented with equivalent networks on the basis of identical input-output transfer characteristics and functional equivalence.

Track circuit mathematical model

To obtain the track circuit mathematical model it is necessary to establish for the track circuit considered the specific physical meaning of the track circuit design parameters, input effects, output responses and environmental factors. The exact expressions of track circuit response and other variables characterising track circuit operation may then be derived by solving the model. Substituting the
above expressions in the general formulation of the above track circuit algorithm yields a system of inequalities which is an exact mathematical description of track circuit operation. In the general case, such an analytical description is quite complicated, involving many variables, so using it for track circuit performance analysis and optimisation may be inefficient. The alternative described here is to directly implement the solution within the computer model.

Computer implementation

Model structure
The model has a modular structure with the following assembled according to the exact track circuit topology:

(a) Long rail track section  
(b) Short rail track section  
(c) Transmitting end track circuit termination  
(d) Receiving end track circuit termination  
(e) Equivalent transmitter  
(f) Equivalent receiver  
(g) Cable

All lumped-parameter modules are modelled at component level, whilst the transmission line (rail track or cable) section modules are described by analytical relationships linking conditions between the two terminals. In addition to physical variables at the terminations, in the long rail track section module, intermediate variables are derived to ensure the user can access physical variables describing the track circuit operation. All the rail track modules incorporate train shunt and broken rail operation, activated through flags set during the specification of the modular structure. This allows different track circuits to be modelled with minimum modification of the model. Adapting the model consists of replacing subroutines describing the terminations.

Solution technique
The solution of the track circuit electric network is based on iterative application of the substitution theorem. The solution process consists of two stages: forward and backward solutions. The first is a stepwise process of calculating the input impedances seen at different points in the track circuit, starting with the receiver and finishing with the transmitter. This enables calculation of the transmitter current, after which backward solution gives all the voltages and currents in the track circuit.

A second computation channel based on the Thevenin method is implemented independently throughout the model which gives computational redundancy. Several key check points for comparing the results for the two channels are available during program debugging and testing.

Validation and Application

The validation strategy is in two parts. The first section is based on continuous monitoring of the accuracy of the model throughout the model building process. This involves the use of proven models and solution techniques. The model structure is kept simple and traceable, and multiple checks of the analytical
Figure 2: Track circuit receiver termination area resonant characteristics of three consecutive track circuits

Figure 3: Effect of track circuit length on transmitter termination area resonant characteristic

Figure 4: Train detection at the boundary between two adjacent track circuits
solutions and computer program are made by introducing redundancy wherever possible and applying approximations only after careful analysis of their effect on model accuracy. The second section involves validation of the overall model by comparison with an established track circuit designed by continuous development. This requires application of the model to simulation of a specific track circuit under various operating conditions.

Concluding remarks

Modelling results obtained with the track circuit simulator described in this paper agree well with known practical results which gives confidence in using the tool for track circuit design and optimisation. The simulation procedure can be used for unshunted, train shunt and broken rail conditions which represents an improvement over existing methods which use balanced track models. To rigorously solve track circuit optimisation problems, a method for searching for optimum solutions according to given criteria is required; this is under development.

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References