Research on wheel rail system based on Dissipative Structure Theory

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Abstract. At present, the research on wheel-rail system is usually to analyze a problem separately, and draw a conclusion through experiments and simulations. This analysis result has certain accuracy, but it often cannot meet the requirements of optimization analysis of wheel-rail complex system. In this paper, by analyzing the characteristics of openness, away from equilibrium and fluctuation of wheel-rail system, a method of constructing element set based on information entropy is put forward. Entropy is used as a parameter to find out the inflow trend of wheel-rail system, and negative entropy flow and positive entropy flow are input to keep the system stable and orderly. The viewpoint of system engineering is put forward for the optimization of wheel-rail system.

1. Introduction
Rail transit is the aorta of national economic development, and its construction is very important to the development of national strength. High speed railway is a complex system [1]. Good wheel rail system environment can improve the speed and running stability of train, which is very important.

In the research of wheel rail system, because of its high degree of system integration, this causes many problems to be very complex. At present, domestic and foreign scholars rarely elaborate on the whole, but studied it from the aspects of wheel rail rolling contact fatigue, wheel rail contact geometry and so on [2-5]. The research on wheel rail system of high-speed railway is mainly limited to engineering technology. Although a single study on a class of problems can obtain accurate analysis, the overall optimal design of the wheel rail system is relatively one-sided. From the macroscopic point of view, applies the theory of dissipative structure in systems engineering, and then analyzes which kind of wheel-rail system can be more stable and optimized.

2. Dissipative structure theory
The application of systems engineering is extensive. Dissipative structure theory, as one of the "three new theories" of system engineering, was founded by Professor Ilya Prigogine. The theory focuses on how the system itself changes from disorder to order, from low order to high order. Its significant [6-7]. In the aspect of high-speed railway, Wen, W. J [8] proposed an effective way to ensure the optimal operation of high-speed railway; Zhang, S. S [9] tried to apply dissipative structure theory to study the evolution mechanism of fault; Xiao, X. M. [10] proposed to use the dissipative structure to study the evolution mechanism of high-speed railway operation faults; Yuan, D. L. [11] applied entropy theory to...
build the management model of dissipative structure of joint test.

2.1 Dissipative structure theory
According to Prigogine, through the system from the outside world of matter and energy exchange, the fluctuation in the process of the system in a certain period of time, the balance of the change of energy parameters reaches a certain value, by implementing the fluctuation, the balance of internal system may also occur stable mutation, the non-equilibrium phase change, gradually developed from the original chaotic state to orderly state of equilibrium.

2.2 Entropy theory
Entropy is the concept of the second law of thermodynamics in physics, which is used to measure the degree of chaos. It originated from thermodynamics, and was later introduced into information theory by Shennong, which can be used as a measure of uncertainty of measurement system state. The information entropy expression of Shennong is [7]:

\[ H(X) = H(p(x_1), p(x_2), \ldots, p(x_n)) = -k \sum_{i=1}^{n} p(x_i) \log p(x_i) \] (1)

Where, \( k \) is a fixed constant; \( x_i \) is the centralized independent possible result of the system; \( p(x_i) \) is the probability of each state.

The concept of entropy can be used to measure the increase and decrease of system functions [12]. Entropy increase weakens the function of the system, entropy decrease strengthens the function of the system, and negative entropy is the active factor that can reduce entropy [13].

3. Dissipative structure characteristics of wheel rail system

3.1 Openness of wheel rail system
The wheel/rail system of high-speed railway is a complex system, which cannot realize the internal self-circulation and must communicate with the outside world constantly.

In the process of train operation, the information between the wheel rail system and the external environment exchanges with each other, making it an open system, the entropy increment is calculated as follows:

\[ dS = deS + diS \] (2)

Where: \( dS \) is the entropy increment of the system; \( deS \) is the entropy exchange quantity between the system and the outside world; \( diS \) is the entropy production quantity in the system.

3.2 Far from equilibrium state of wheel rail system
Prigogine argued that dissipative structures can only occur when the system is "far from equilibrium." The internal subsystems and optimization elements of the high-speed train wheel/rail system change unevenly, so there will be potential differences in their effects on the railway wheel/rail system. It follows the Ansager reciprocity relationship, as shown in Formula 3:

\[ \sigma = \sum_{i} X_i J_i (i = 1, 2, 3, \ldots) \] (3)

Where: \( \sigma \) is the entropy yield per unit volume of medium in the system; \( X_i \) is a generalized thermodynamic force in the irreversible process; \( J_i \) is the generalized thermodynamic rate in the irreversible process of the system.

3.3 Fluctuation of wheel rail system
The problem of wheel rail system is often caused by the amplification of micro fluctuation (such as slight rail corrugation) into giant fluctuation (severe shock vibration) under the nonlinear action (bad weather and driving in alpine regions).

The wheel rail system of high-speed railway has three necessary conditions to form dissipative
structure, so the optimization of wheel rail system of high-speed railway can be studied by dissipative structure theory.

4. Construction of wheel rail system element set based on information entropy
In order to meet the requirements of the wheel/rail system, it is necessary to provide stability and comfort conditions, but also to ensure that the high-speed train and the components on the track have some stability, so that they can work well.

4.1 Rough set theory
Rough set theory is a tool to deal with uncertainty in mathematics and a scientific method to deal with uncertainty. The optimization element set of high-speed railway wheel rail system is defined as condition attribute. The construction method of wheel rail system element set based on information entropy is proposed: let the stable state of high-speed railway wheel rail system be[10]

\[ S =< U, C \cup D > \]  

Where:
- \( U \) is the universe of the wheel rail system;
- \( C \) is the optimization element set;
- \( D \) is the typical failure of the wheel rail system.

4.2 Optimization of discrete elements
The optimization factors of the track system include continuously variable speed and track smoothness, etc. In the high-speed rail wheel/rail system, the values of continuous variables should be discretized. Naive Scaler discretization algorithm is used to process the continuous variables of high-speed railway wheel/rail system elements.

The calculation process is as follows:
1. According to the attribute values of the optimization elements, the instances are arranged in the order from small to large \( x_i \in U \).
2. Scanning from small to large, let \( x_i, x_j \) represent two adjacent instances. If yes, continue scanning, where and are the values of instance and on. If \( d_i(x_i) = d_i(x_j) \), that is, the decision is the same, continue to scan, where \( d_i(x_i) \) and \( d_i(x_j) \) are the values of \( x_i \) and \( x_j \) on \( d_i \); Otherwise, we get a breakpoint \( c \)

\[ c = 1/2[ a(x_i) + a(x_j) ] \]  

The discrete attributes are 0, 1, 2 Assign values.

4.3 Construction of typical fault optimization element set
We take the optimization element as the initial condition attribute set, and use conditional information entropy [14] to reduce the optimization element \( C \):
1. Calculate the conditional entropy \( S_C(D|C) \) of typical fault set \( D \) for optimization element set \( C \).
2. The conditional entropy \( S_C(D|\{a_i\}) \) of typical fault set \( D \) relative to each optimization element is calculated, and the optimization elements are arranged in SGF \((a_i, A, D) \) descending order to get queue \((a_i)\).
3. Let \( B = C \) and give the important threshold of attribute \( \varepsilon \).
4. Repeat the following steps until attribute set \( B \) no longer changes.
   1. Take the first optimization element \( a_i \) of queue \((a_i)\) and delete it from the queue.
   2. The conditional entropy \( S_C(D|B-\{a_i\}) \) of typical fault D pair and B is calculated after deleting \( a_i \) of optimization element set \( B \).
   3. If \( S_C(D|C) = S_C(D|B-\{a_i\}) \), It shows that the optimized elements \( a_i \) are redundant and should be reduced, \( B = B \setminus \{a_i\} \);
   4. If \( 0 < S_C(D|B-\{a_i\}) - S_C(D|C) < \varepsilon \), indicating that the optimization factor \( a_i \) is not important, and the reduction \( B = B \setminus \{a_i\} \).
5. Realization of dissipative structure theory in wheel rail system

5.1 Entropy calculation model

In order to realize the optimization of the high-speed railway wheel/rail system, combined with the above research and the entropy calculation model proposed by AO, S.Y. [15], the entropy calculation model of the high-speed railway wheel/rail system is given as follows:

1) Calculate the entropy flow value of single optimization factor \( S_i \)

\[
S_i = -x_i \ln x_i
\]  
(6)

Where:
- \( S_i \) is the entropy flow value generated by optimization factor \( a_i \); 
- \( x_i \) is the number of 100 km overruns and unqualified rate of optimization factor \( a_i \).

2) The typical fault optimization element set is selected and the level matrix \( A = (a_1, a_2, ..., a_i, ..., a_n) \) is constructed.

3) Construction of typical fault optimization elements interaction matrix \( B \)

\[
B = \begin{pmatrix}
  b_{11} & b_{12} & \cdots & b_{1n} \\
  \vdots & \ddots & \vdots & \vdots \\
  b_{n1} & b_{n2} & \cdots & b_{nn}
\end{pmatrix}
\]  
(7)

4) The weight matrix \( C = [\omega_1, \omega_2, ..., \omega_n]^T \) of each optimization element is constructed.

among

\[
c_i = \frac{SGF(a_i, A, D)}{\sum_{i=1}^{n} SGF(a_i, A, D)}
\]  
(8)

5) Calculation of total entropy \( S \) of high speed railway wheel rail system

\[
S = A \times B \times C
\]  
(9)

5.2 Fault evolution mechanism

According to the bifurcation phenomenon of dissipative structure, that at first the wheel rail system of high-speed railway is in a stable state, but with the change of time and the fluctuation characteristics of the system, there are three possibilities for the system, as shown in Figure 1.

(1) When the total entropy \( S > 0 \), the disorder effect produced by the positive entropy is greater than the order effect produced by the negative entropy, and the general trend of the system is unstable.

(2) If \( S = 0 \), the ordered and disordered tendencies of the system are equivalent, that is, in equilibrium, the ordered and disordered tendencies of the system cancel each other out.

(3) When \( S < 0 \), the negative entropy of the system cancels out the positive entropy, so that the total entropy of the system decreases to a negative value. The ordered effect produced by the negative
entropy is greater than the disordered effect produced by the positive entropy, making the trend of the system orderly and stable.

6. Conclusion
Taking the wheel rail system of high-speed train as the research object, this paper uses the theory of dissipative structure to explain the optimization of the wheel rail system:

(1) By analyzing the openness, far from equilibrium state and fluctuation characteristics of the wheel rail system, it is concluded that the wheel rail system of high-speed train has the necessary conditions to form a dissipative structure, so the wheel rail system of high-speed railway is a dissipative structure, and its optimization can be studied by using the dissipative structure theory.

(2) Based on dissipative structure and entropy theory, the evaluation of wheel rail system of high-speed railway is studied. The entropy flow model and entropy calculation method of wheel rail system of high-speed railway are given. The reliability of wheel rail system of high-speed railway can be comprehensively analyzed by entropy calculation.

(3) Through the dispersion phenomenon of dissipative structure, the fault evolution mechanism of high-speed railway wheel rail system is explained. Strengthening negative entropy and reducing positive entropy can achieve the prevention of wheel rail system fault.

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