Research on Structural reliability and reliability sensitivity of EMU pantograph

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Abstract. Due to the uncertainty of the contact state between the pantograph and the power grid when the EMU is running at high speed, as well as the influence of road conditions and environment, the external load applied to the pantograph and the material properties of the pantograph have certain randomness, thus affecting the current collection quality of the pantograph and the service life of the carbon slide plate. Taking a certain type of EMU single arm pantograph as the research object, a three-dimensional model is established, ANSYS Workbench software is used to carry out the finite element analysis to determine the dangerous point and its stress response; the simulation samples of material properties and stress of dangerous points are obtained by using sampling method and test design method based on the principle of normal distribution; the reliability index and reliability of pantograph structure strength are analyzed, based on the random perturbation method and the first-order second-moment method, and using the simulation sample data extracted by Latin hypercube sampling, and the reliability accuracy is verified by Monte Carlo method. Based on the definition of reliability sensitivity, the influence degree of each input variable on the reliability change of pantograph structure is determined as follows: external load > Poisson's ratio > material density > elastic modulus, which provides reference for improving the reliability, service life and structural optimization design of pantograph.

Keywords. pantograph; finite element analysis; random perturbation method; Monte Carlo; reliability; reliability sensitivity

1. Introduction
With the development of “the Belt and Road Initiatives”, High-speed railway development and stable operation will be the inevitable trend of railway development. At the same time, railway electrification is a prerequisite for ensuring high-speed and stable operation of trains[1,2]. The pantograph is an extremely important electrical component in the traction system of high-speed trains. It is used to conduct electrical energy from the catenary to high-voltage equipment in high-speed trains. Due to the uncertainty of the pantograph structure and the catenary structure, the parameters such as the external load and material properties of the pantograph have a certain randomness, which affects the current collection quality of the pantograph[3-5], so, it is necessary to analyze the structural reliability of the pantograph.
In order to solve the problem of high-speed current collection of pantograph, make the pantograph receive reliable and stable current when the EMU is running at high speed, and ensure that the pantograph provides stable electrical energy for the high-speed running EMU. Liu S B [6] proposed that the horizontal tension of the catenary will increase with the increase of speed, thus affecting the quality and reliability of the current collection between the pantograph and the catenary; Ma S Q [7] conducted a static strength analysis on the pantograph finite element model with wind resistance contact force and verified its reliability; Wang Y F [8] based on the historical failure data of pantograph, used the reliability data analysis method to find the weak link of pantograph system reliability. In reality, in addition to the running speed and external load, the randomness of the pantograph's material properties has an important influence on the pantograph's current collection quality [9-11].

Taking a single-arm pantograph as a research object, ANSYS finite element analysis software is used to establish a finite element model and perform static strength analysis to obtain the location of the dangerous point and the stress value of the dangerous point. Combining sampling methods and experimental design methods, simulation samples of dangerous point stress and random parameters are obtained. Based on the random perturbation method and the first-order second-moment method, the static strength reliability analysis of the pantograph structure is performed. And use Monte Carlo method to test the error of the static strength reliability of the pantograph structure. Through reliability sensitivity analysis, the importance of random parameters to the reliability of pantograph structure is determined, which provides ideas for reliability design and structural optimization design of pantograph structure.

2. Introduction of pantograph structure

As an important component on the EMU, the pantograph is responsible for transferring the electric energy from the catenary to the traction motor on the EMU to drive the EMU to run quickly. The single-arm pantograph is selected as the research object. Its structure includes collector head, upper arm, lower arm, connecting rod and underframe.

During the running of the high-speed train, the pantograph underframe is fixed on the top of the train, and the collector head contacts the catenary to obtain electrical energy. According to the actual working conditions, the force situation of the pantograph is shown in Figure 1.

![Figure 1. Analysis of pantograph force situation.](image)

The contact pressure between the pantograph and the catenary can be calculated by the following formula:
\[ F_c = F_{c0} + F_a + M_a a \]  

(1)

- \( F_c \) --- External load
- \( F_{c0} \) --- Static contact pressure
- \( F_a \) --- Air lift during pantograph operation
- \( M_a \) --- Dynamic contact force between pantograph and catenary
- \( M_a a \) --- Dynamic weight during pantograph operation
- \( a \) --- Vertical acceleration

For the pantograph overall system, when the pantograph is raised and stationary, its load is mainly the static contact force between the pantograph and the catenary. During the operation of the system, its load increases the dynamic contact force and aerodynamic force between the pantograph and the catenary.

### 3. Finite element analysis of static strength of pantograph structure

According to the two-dimensional engineering drawing of the pantograph of a certain EMU, the three-dimensional solid model of the pantograph is established using Creo 3D modeling software. In the ANSYS workbench finite element analysis software, the four-node or five-node tetrahedral elements are used to perform high-quality finite element meshing of the pantograph, set a reasonable element size and density, and generate a total of 206607 nodes and 301720 elements. The pantograph finite element model is shown in Figure 2.

![Pantograph finite element model](image)

**Figure 2.** Pantograph finite element model.

The materials and mechanical properties of the components of the pantograph structure are shown in Table 1.
Table 1. Materials and mechanical properties of components.

| Components      | Material          | Yield strength/MPa |
|-----------------|-------------------|--------------------|
| Underframe      | Stainless steel   | 207                |
| Connecting rod  | Stainless steel   | 207                |
| Lower arm       | Carbon steel(Q235)| 235                |
| Upper arm       | Aluminum alloy(5083) | 125            |
| Collector head  | Aluminum alloy(5083) | 125            |

According to the design requirements of the relevant standards, the load of the pantograph is applied at the position of the collector head, taking into account the vertical force generated between the catenary and the carbon slide, and the longitudinal friction between the carbon slide and the catenary and the aerodynamic load on the pantograph.

1) Vertical load

The official provides standards for the strength design of the catenary, which specifies the maximum contact force between the pantograph carbon slide and the catenary when the train is running at the maximum running speed\(^{[12]}\), such as Table 2 shows.

Table 2. Range of contact force between pantograph and catenary.

| Current form      | Running speed (km/h) | Maximum contact force (N) |
|-------------------|----------------------|---------------------------|
| Alternating current | ≤200                 | 300                       |
| Alternating current | >200                 | 350                       |
| Direct current    | ≤200                 | 300                       |
| Direct current    | >200                 | 400                       |

It can be seen from Table 2 that considering the actual operating condition of the EMU train running speed of 350km/h, a pressure of 350N in the vertical and downward direction is applied at the center of the pantograph carbon slide.

2) Longitudinal load

The longitudinal load on the pantograph mainly considers the friction between the pantograph and the catenary. The friction is related to the vertical load and the coefficient of friction. The longitudinal load on the pantograph mainly considers the friction between the pantograph and the catenary. The friction is related to the vertical load and the coefficient of friction. According to the actual situation, a longitudinal load of 450N is applied to the part where the catenary contacts the pantograph, that is, the centerline of the pantograph carbon slide.

3) Aerodynamic load

As the running speed of the train increases, the air flow has a greater and greater impact on the pantograph. In addition, the operating speed of the current high-speed trains has far exceeded the 200km/h given in the standard, so the aerodynamic effect should be taken into account when performing strength analysis on the pantograph. Therefore, the pressure of 6000Pa is added to the entire side of the pantograph carbon slide to simulate the aerodynamic resistance of the EMU train during operation.

According to the load distribution of the relevant working conditions, apply force to the pantograph finite element model, and use ANSYS finite element analysis software to calculate the overall static strength of the pantograph. The overall equivalent stress of the pantograph is shown in Figure 3. The location of the maximum stress point of the pantograph is shown in Figure 4.
Figure 3. The overall equivalent stress of the pantograph.

Figure 4. The location of the maximum stress point of the pantograph.

It can be seen from Figure 4 and Figure 5: The location of the maximum stress occurs at the connection position of the underframe and the lower arm, the size is 189MPa, which is smaller than the yield limit of the lower arm material, carbon steel (Q235), 235MPa, but the gap is relatively small. In actual working conditions, some structural parameters and forces of the pantograph will change, so that
the maximum stress may be close to or even exceed the yield limit of the material, so it is necessary to further analyze the reliability of the structure.

4. Reliability analysis of pantograph structure

4.1. Reliability analysis based on random perturbation method

According to the stress-intensity interference theory, the limit state equation of the pantograph is established, and its reliability analysis model can be expressed as:

\[ Z = g(X_1, X_2, X_3, \ldots, X_i) = [\sigma] - \sigma_{\max} \]  \quad (2)

When \( Z \geq 0 \), the pantograph structure is reliable;  
When \( Z = 0 \), the pantograph structure is in the limit state;  
When \( Z < 0 \), the pantograph structure fails.

\( X_i \) ---- Random Variables. Refers to the external load parameters of the pantograph and the material parameters of the pantograph lower arm;  
\( g(X) \) ---- State function. Refers to the state of safety or failure of parts;  
\([\sigma]\) ---- The intensity of the danger point. Refers to the yield limit of the pantograph lower arm material.  
\( \sigma_{\max} \) ---- Equivalent stress value of dangerous point. Refers to the stress on the dangerous point of pantograph.

In the actual situation, due to the existence of design tolerances, processing deviations, changing environments and other factors, the parameters such as the external load and material properties of the pantograph have a certain randomness [13-14]. All these will affect the driving force of the train and have an important impact on the high-speed and stable operation of the train.

Therefore, pantograph contact pressure, elastic modulus, Poisson's ratio and material density are selected as random variables. According to a large number of measured data and simulation results, random variables, variable symbols and other parameters are shown in Table 3.

**Table 3.** Characteristics of random variables.

| Random variables                  | Variable symbol | Average | Standard deviation |
|-----------------------------------|-----------------|---------|--------------------|
| External load/N                   | \( F_c \)       | 350     | 10.5               |
| Elastic modulus/MPa               | \( E_s \)       | 21000   | 2500               |
| Poisson's ratio                   | \( \mu \)       | 0.3     | 0.025              |
| Material density/kg/mm-3 \( \rho \)|                 | 7.85\times 10^{-6} | 0.42\times 10^{-6} |

According to Latin hypercube sampling, 100 sample points were taken as input samples of random variables, and 100 static strength calculations were performed to obtain 100 corresponding output samples. All sample data are shown in Table 4.

**Table 4.** Sample data.

| Serial number | \( F_c / N \) | \( E_s / \text{MPa} \) | \( \mu \) | \( \rho / \text{kg/mm}^3 \) | \( \sigma_{\max} / \text{MPa} \) |
|---------------|---------------|------------------------|---------|----------------|-----------------|
| 1             | 321.422       | 2.035\times 105        | 0.315   | 7.952\times 10^{-6} | 174.523         |
According to the random perturbation method, $X$ and $g(X)$ can be expressed as:

$$X = X_d + eX_p$$

(3)

$$g(X) = g_d(X) + eg_p(X)$$

(4)

$\varepsilon$ ---- Tiny parameter. $|\varepsilon| \leq 1$.

d---- The determined part of the random variable.

p---- The random part of the random variable.

Obviously, the random part is required to be much smaller than the determined part, then the mathematical expectation of equations (3) and (4) is:

$$\mu_s = E[g(X)] = E[g_d(X)] + eE[g_p(X)] = g_d(X)$$

(5)

Combining Kronecher algebra theory and related stochastic analysis theory, taking the second order moments on both sides of formula (3) and formula (4), the expression is

$$\sigma_s^2 = Var[g(X)]$$

$$= \varepsilon^2 E\left[\left[\frac{\partial g_d}{\partial X^T}\right]^{[2]} X_p\right]$$

(7)

According to the first-order second-moment method, the reliability index can be expressed as

$$\beta = \frac{\mu_s}{\sigma_s} = \frac{E[g(X)]}{\sqrt{Var[g(X)]}}$$

(8)

When the random variables follow a normal distribution, the reliability is expressed as

$$R = \phi(\beta)$$

(9)

Among them, $\phi$ is the standard normal distribution function, according to formula (8) and formula (9), the reliability index and reliability of the pantograph are calculated as

$$\beta = 3.142$$

$$R = 0.9992$$

4.2. Error detection according to Monte Carlo

|   |       |         |         |         |         |
|---|-------|---------|---------|---------|---------|
| 2 | 327.561 | 2.259×10^5 | 0.308 | 8.049×10^{-6} | 174.864 |
| 3 | 330.895 | 2.091×10^5 | 0.304 | 7.883×10^{-6} | 175.168 |
| 4 | 333.278 | 2.168×10^5 | 0.298 | 7.797×10^{-6} | 175.464 |
| ... | ... | ... | ... | ... | ... |
| 97 | 369.684 | 2.116×10^5 | 0.304 | 7.842×10^{-6} | 200.097 |
| 98 | 370.964 | 2.086×10^5 | 0.328 | 7.796×10^{-6} | 200.433 |
| 99 | 375.312 | 2.069×10^5 | 0.295 | 7.869×10^{-6} | 200.752 |
| 100 | 383.596 | 2.012×10^5 | 0.316 | 8.061×10^{-6} | 201.065 |
Monte Carlo method is also called statistical test method or random sampling method. The basic idea is to obtain the probability of an event or the expected value of a random variable by designing an experiment, and use them as an approximate solution to the problem [15].

The Monte Carlo method calculates the failure probability by substituting random samples into the limit state equation and recording the number of sample points that fall into the failure domain. The variance of the failure domain indicator function is the failure probability.

The failure probability can be expressed as

\[ P_f = \frac{N_f}{N} \tag{10} \]

Structural reliability can be expressed as

\[ R = 1 - P_f \tag{11} \]

According to the Monte Carlo simulation method, using MATLAB software programming, the reliability is obtained after 104 calculations as

\[ R_M = 0.9994 \]

Compared with the reliability results obtained by the first-order second-moment method, the relative error is

\[ \varepsilon_R = \frac{|R - R_M|}{R_M} = 0.2002 \times 10^{-3} \tag{12} \]

It can be seen that the relative error of the two calculation results is very small, so the reliability of the pantograph structure calculated by the second-order moment method is relatively accurate.

5. Analysis of reliability sensitivity

The reliability sensitivity analysis of pantograph structure is to study the influence of the change of external load and material properties of random input variables on the reliability change of pantograph structure, which is a very important part of structural reliability analysis.

The partial derivative of reliability to distribution parameters of basic variables is reliability sensitivity. Based on the relationship between reliability and reliability index, and between reliability index and distribution parameters of basic random variables, the sensitivity of reliability to mean value and standard deviation of each random variable can be obtained as

\[
\frac{\partial R}{\partial \mu_{X_i}} = \frac{\partial R}{\partial \beta} \frac{\partial \beta}{\partial \mu_{X_i}} \\
\frac{\partial R}{\partial \sigma_{X_i}} = \frac{\partial R}{\partial \beta} \frac{\partial \beta}{\partial \sigma_{X_i}} \tag{13}\]

And

\[
\frac{\partial R}{\partial \beta} = \varphi(\beta) = \frac{1}{\sqrt{2\pi}} \exp\left( -\frac{1}{2} \beta^2 \right) \tag{15} \]

\[
\frac{\partial \beta}{\partial \mu_{X_i}} = \frac{1}{\sigma_g} \tag{16} \]

\[
\frac{\partial \beta}{\partial \sigma_{X_i}} = \frac{\mu_g}{\sigma_g^2} \tag{17} \]

The reliability sensitivity of reliability to four basic random variables with respect to mean and standard deviation can be obtained by substituting the calculation results of pantograph reliability and the relevant data of each random parameter into equation (13) and equation (14). For the units of random
parameters are different, there is no comparability between reliability sensitivity, so it is necessary to dimensionless the reliability sensitivity results:

\[
\frac{\partial R}{\partial \mu_x} \sigma_s = \begin{bmatrix}
R_E(F_c) \\
R_E(E_x) \\
R_E(\mu) \\
R_E(\rho)
\end{bmatrix} = \begin{bmatrix}
-2.8667 \\
0.0479 \\
-0.4213 \\
0.1373
\end{bmatrix}
\]

(18)

\[
\frac{\partial R}{\partial \sigma_x} \sigma_s = \begin{bmatrix}
R_\sigma(F_c) \\
R_\sigma(E_x) \\
R_\sigma(\mu) \\
R_\sigma(\rho)
\end{bmatrix} = \begin{bmatrix}
-8.1864 \\
-0.0273 \\
-0.1052 \\
-0.0498
\end{bmatrix}
\]

(19)

Through sensitivity analysis, the importance of each random input variable to the output response can be obtained. It can be seen from the calculation results that the most important factor affecting the reliability of pantograph is external load \( F_c \), followed by the relevant parameters of material properties: Poisson's ratio \( \mu \), material density \( \rho \) and elastic modulus \( E_x \). With the demand and development of high-speed stability of railway, the contact pressure should be considered as the primary factor in the design of pantograph. In order to ensure the stable operation of pantograph, vibration reduction measures should be taken to reduce the dynamic contact pressure between pantograph and catenary. If it is necessary to adjust the material to ensure sufficient reliability, the influence of Poisson's ratio of material on reliability is preferred.

6. Conclusion
The high-voltage traction system of EMU is one of the key factors related to train operation safety. In order to ensure the safe operation of high-speed EMU, comprehensive comparative analysis is needed from the perspective of reliability. In this paper, the pantograph in the traction system of high-speed EMU is taken as the research object. The reliability analysis, inspection and reliability sensitivity analysis of pantograph are carried out based on the stochastic perturbation technique, first-order second-moment method and Monte Carlo method. The results show that the external load \( F_c \) is the most important factor affecting the reliability of pantograph, followed by the relevant parameters of material properties: Poisson's ratio \( \mu \), material density \( \rho \) and elastic modulus \( E_x \). In order to ensure the stable and reliable operation of pantograph, priority should be given to reducing the external load between pantograph and catenary. The increase of train speed will lead to the increase of air lift. Therefore, measures should be taken to reduce the vibration to reduce the dynamic contact pressure between pantograph and catenary; at the same time, the reliability of pantograph can be improved by changing the material properties and reducing the standard deviation of elastic modulus, Poisson's ratio and material density. Reliability and reliability sensitivity analysis can be used as the guidance of practical engineering design. According to the analysis results, we can modify the influential factors to carry out reliability design and structural optimization design, and provide ideas for practical engineering design.

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