Damage analysis of EMU frame considering randomness under different working conditions

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ABSTRACT. *The target of this study was to investigate the stress changes of frame when the EMU train passed the mainline, or the curve line in the EMU section, or the branch line of turnouts. In this regard, the author adds a MEMS gyroscope and GPS equipment to the conventional dynamic stress test, and proposes a working condition identification scheme based on curvature determination to obtain line information. Considering the randomness of the damage, in the analysis process, the equivalent stress is regarded as a random variable, and its distribution characteristics are discussed to make the results more real and reliable. The results of quantitative analysis of the damage indicated that some working conditions on the mainline contribute to the frame damage to a certain extent, and when the train passes through small turnouts and curves in the depot at a low speed, the amplitude of stress is several times higher than the high speed straight line working condition. The findings of this study may serve as a basis for further establishment of the load spectrum of working conditions, and provides references for fine design in the aspect of vehicle reliability.*

RÉSUMÉ. *L'objectif de cette étude était d'examiner les modifications de la contrainte de la trame lorsque le train de l'EMU dépassait la ligne principale, ou la courbe de la section EMU, ou l'embranchement des aiguillages. À cet égard, l'auteur ajoute un gyroscope MEMS et un équipement GPS au test de contrainte dynamique classique et propose un schéma d'identification des conditions de travail basé sur la détermination de la courbure pour obtenir des informations sur les lignes.Compte tenu du caractère aléatoire des dommages, dans le processus d'analyse, le stress équivalent est considéré comme une variable aléatoire et ses caractéristiques de distribution sont discutées pour rendre les résultats plus réels et fiables.Les résultats de l'analyse quantitative des dommages indiquent que certaines conditions de travail sur la ligne principale contribuent dans une certaine mesure aux dommages au cadre. Lorsque le train passe à faible vitesse de virage et se courbe dans le dépôt, l'amplitude de la contrainte est de plusieurs fois plus élevé que la condition de travail en ligne droite à grande vitesse.Les résultats de cette étude peuvent servir de base à l'établissement ultérieur du spectre de charge des conditions de travail et constituent des références pour une conception soignée en ce qui concerne la fiabilité du véhicule.*

KEYWORDS: *EMU, frame, dynamic stress test, working condition identification, fatigue strength evaluation, damage randomness.*

MOTS-CLÉS: EMU, cadre, test de stress dynamique, identification des conditions de travail, évaluation de la resistance a la fatigue, dommage au hasard.

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1. Introduction

In recent years, the increase in the speed of EMUs has placed higher demands on the reliability of the overall vehicle system (Wang *et al.*, 2009; Franco *et al.*, 2007). The bogie frame of the EMU is a key part of its running gear. It is an “H” structure consisting of two box-type side-beams and two cylindrical cross-beams. During its service, fatigue strength evaluation of welds and stress concentrations is a must. The results of frame damage status obtained by direct measurement of the dynamic stress response under frame operation conditions are more real, more reliable, and with more sufficient evidences (Lu *et al.*, 2010; Yu *et al.*, 2011) than the results obtained by bench test or finite element simulation which are conducted according to existing railway standards such as AAR, JIS and UIC, etc.

A large number of dynamic stress tests conducted on different lines of different vehicle frames have been completed in recent years (Luo *et al.*, 1996; Deng *et al.*, 2008; Dietz *et al.*, 1998). However, there are few studies on the stress state changes of the EMU structure under special working conditions. In order to clarify the influence of line conditions and speed grades on the fatigue of the frame, this paper makes an in-depth study of the dynamic stress characteristics of the key points on a certain frame under the above-mentioned working conditions. In the vehicle equipment compartment where the test frame is located, micro-mechanical (MEMS) gyroscope, GPS and other sensors for identifying road conditions are installed, and a working condition discriminant model based on the curvature radius is proposed.

Due to the short stress data measured under certain typical working conditions, the stress performance of some location points is still significantly different under the same working condition, or when the EMU passes through the same section at the same speed. The damage status calculated with this result must be random, which is quite common in the study of damage. Based on the random phenomenon of such dynamic stress response and conventional stress equivalent scheme, a correction scheme for damage consistency is proposed in this paper, so that the fatigue evaluation conclusion of the frame under different working conditions is more reliable.

This paper consists of 4 parts. The first part introduces the dynamic stress test and the method of working condition characteristics extraction. The second part gives an improvement of the damage assessment program. The third part calculates the damage of the frame under different working conditions according to the optimization scheme. Finally, the conclusion is given.

2. Frame dynamic stress test and working condition characteristics extraction

2.1. Dynamic stress test

In order to accurately assess the key structural reliability of this type of EMU bogie frame and provide a basis for setting the overhaul period of key structures, a large number of strain sensors are placed on the typical key welds of bogie frame of this train. Long term dynamic stress tracking tests have obtained stress data covering various speed grades and various railroad characteristics, other sensor data for assisted working condition identification was obtained as well.

The signals collected by the equipment usually contain a lot of interference and noise. Generally, it is necessary to remove the glitches and filter out the inherent interference band such as white noise. The zero drift of data due to the influence of the device itself and the surrounding environment needs to be removed at the same time. All kinds of data need to be multiplied by corresponding coefficients to obtain true stress and angular velocity. For dynamic stress data, before compiling the stress spectrum, it is necessary to take out all the stress cycles by rain-flow counting method to facilitate stress equivalence and damage assessment (Amzallag *et al.*, 1994).

2.2. Example of working condition characteristics extraction

When identifying the curves and turnouts based on the radius of curvature, the vertical axis of the gyroscope is the sensitive axis. Attribute the vibrations caused by the intersection of two trains, passing through tunnels, turnouts or the steel rails, and other factors to random events that affect the results, when ignoring ultra-high of the curve, the data of the vertical axis of the gyroscope can directly reflect the angular velocity on the horizontal surface of the gyroscope attachment position in the equipment compartment. According to the principle of rigid body kinematics, since the gyroscope is close enough to the frame to be tested, it can be considered that the attachment position angular velocity is equal to the frame instantaneous angular velocity.

For gyroscope data with larger interference in some special experiments, there are wavelet transform and other denoising methods (Grinsted *et al.*, 2004). In this paper, after the gyroscope data is processed by low-pass filtering, zero-drift removing and other steps, when comparing the obtained curve line turnout parameters with part of the existing line data, certain parameters are allowed within a certain error range, the working conditions can be matched one by one. Figure 1 shows the comparison of the raw data and processed data of gyroscope in a section.

Combine the stress data pre-processing method and refer to the reference (Johnn *et al.*, 2009) for the suggestion of zero-drift treatment, and substitute the sensitivity of the gyroscope S = 13.3mV/°/s to obtain the results in Figure 1.

Among them, AB segment and CD segment are two complete curve data. By intuitive judgment, when passing through the EG segment, the absolute value of the angular velocity is significantly increased, and this segment might be an S-curve with a small radius of curvature. Query the line data of this segment, EG segment is the lateral passing through of the No. 18 turnout. After calculation and analysis, the data segment in Figure 1 comes from the lines shown in the figure below.

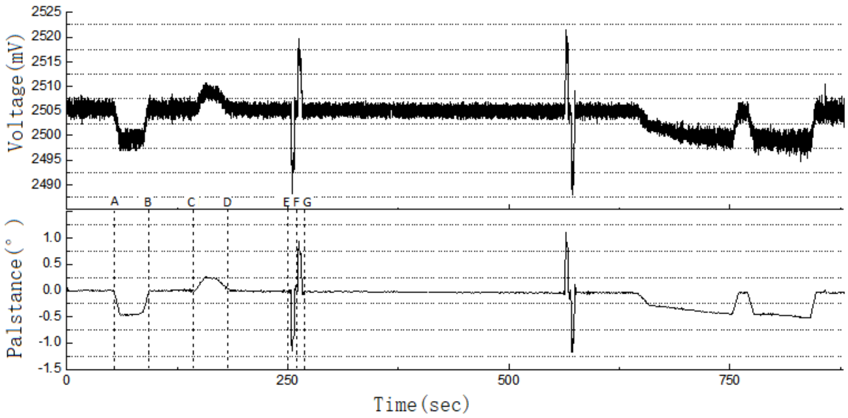

Figure 1. Gyroscope raw data and processed data contrast.

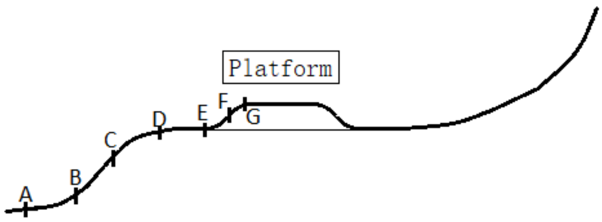

Figure 2. Schematic diagram of corresponding railway line of the gyroscope data.

Furthermore, in the working condition discrimination based on the curvature, the radius of curvature to be calculated first is obtained by the following equation:

$$r = \frac{360 \times v}{2\pi\omega} \tag{1}$$

Where v is the instantaneous line speed measured by the GPS. After calculation, the two waists of the data segment similar to the trapezoidal curve in the figure are the commonly used cubic parabola-like transition curves, and the trapezoidal upper end is usually a circular curve segment. Some trapezoidal-like data segments are irregular, which is generally caused by changes in the line speed.

The rotation angle and actual running distance of the train when passing the curve are:

$$\theta = \int \omega(t) d(t) \tag{2}$$

$$L = \int v(t) d(t) \tag{3}$$

Using the above three equations, the radius of the curve for the EF and FG segments was calculated to be 1195m and 1243m, respectively. The radius of the standard circle curve of the 18th turnout is 1100m, which is far from the minimum value (≥7000m) of the curve radius on the mainline under normal conditions. Therefore, it is effective to use the curvature radius value to identify the curves and the turnouts.

In order to facilitate the quantitative analysis, according to partial line data, we extract 30 sets of gyroscope data from each of the 18th turnout, part of the 12th turnout in the depot and the 9th turnout, and then perform normality and distribution fitting on their radius respectively (Brown, 1974), according to the 3σ principle, the discrimination basis is given:

Table 1. Discrimination basis of different types of turnouts.

Turnout type	Standard radius (m)	Discrimination basis (m)
No.9	180	[138,254.6]
No.12	350	[291.7,470.8]
No.18	1100	[967.4,1395.1]

3. Damage assessment scheme optimization

3.1. Routine damage assessment method

The conventional damage assessment method of the frame is based on the Miner linear cumulative damage rule, which converts the stress at all measuring points into the equivalent stress with constant amplitude under a certain number of cycles.

First of all, the damage D_1 caused by a certain stress spectrum under a certain number of kilometers is as follows:

$$D_1 = \sum_{i=1}^{n} \frac{n_i}{N_i} = \sum_{i=1}^{n} \frac{n_i \sigma_i^m}{C_1} \tag{4}$$

In above equation, n_i is the number of cycles at the i-th stress level, N_i is the fatigue life corresponding to the i-th stress amplitude, σ_i is the i-th stress spectrum amplitude, and m and C_1 are the S-N curve parameters.

When the applied time of equivalent stress amplitude σ_e is N, the damage of the structure is D. There is:

$$D = \frac{N\sigma_e^m}{C_1} \tag{5}$$

Where, N is the number of cycles corresponding to the fatigue limit of the parent material. For the welded frame, it usually takes 2×10^6 times.

Set the running mileage under the known measured stress spectrum as L_1, the damage caused by the stress spectrum is D_1, and the safe running mileage for damage D is L, then:

$$\frac{D}{L} = \frac{D_1}{L_1} \tag{6}$$

Substituting equations (4) and (5) into the above equation, the equivalent stress can be obtained as follows:

$$\sigma_e = \left(\frac{L}{L_1 N} \sum n_i \sigma_i^m\right)^{1/m} \tag{7}$$

Calculate according to designed service life 12 million km of the EMU in China, substitute the stress spectrum obtained from the test of a certain section, then we can get the corresponding equivalent stress.

3.2. Randomness of damage

In the process of studying the influence of different working conditions on the damage of key points on the frame, 5 representative measuring points of a certain type of EMU were selected for the damage analysis, locations of these points include the joint of the small longitudinal-beam and cross-beam on the train frame, the joint of brake hanger and the cross-beam, the joint of cross-beam and side-beam, etc. The specific locations are shown in the following figure:

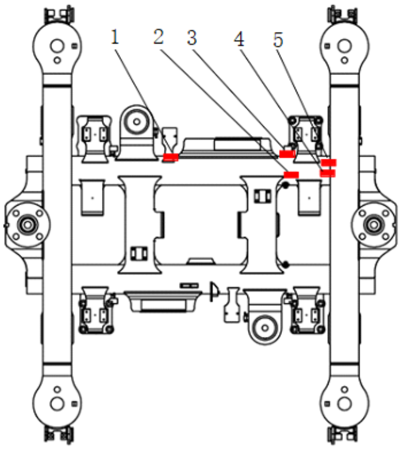

Figure 3. Location map of key points on the frame.

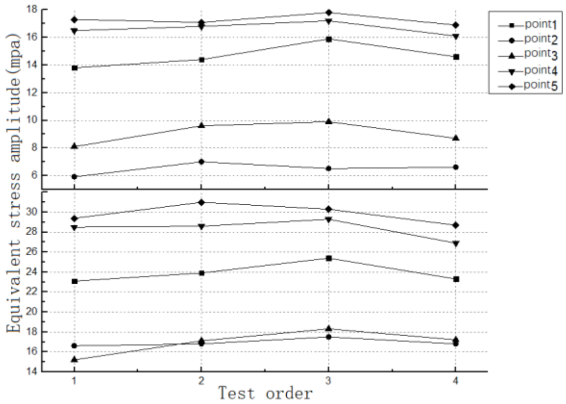

Figure 4. Comparison of equivalent stress of the four tests at key points when passing the curve and turnouts.

Extract the dynamic stress data of 5 measuring points from the AB curve in Figure 1 and the EF turnout where the EMU has passed through 4 times within 1 month. According to the equivalent stress calculation method in 2.1, the obtained results are compared as shown in the following figure.

In Figure 4, the above and below two graphs are the calculated results of the equivalent stress when passing AB curve and EF turnout respectively. It can be seen that, for the same measuring point, when it passes the same line section twice, the equivalent stress is still different. For example, for the measuring point 3 which is located at the joint of brake hanger and the cross-beam, when it passes the turnout for three times, its equivalent stress of the third time is increased by 20% from the first time. From this, it can be seen that, there may be randomness and errors when using the equivalent stress value of one specific test to evaluate the damage degree of key points under this working condition.

3.3. Equivalent stress correction algorithm

In view of the existing problem of stress amplitude fluctuation, we now try to divide the whole life span mileage L of the frame into several small segments. According to equation (7), the damage value D_i of the i-th segment can be obtained as follows:

$$D_i = \frac{\sigma_{ei}^m N L_i}{C_1 L} \tag{8}$$

Where σ_{ei} is the equivalent stress amplitude of the i-th segment, and L_i is the corresponding mileage. Therefore, accumulating all D_i is the damage D of the whole life span mileage.

Since the ratio of each small segment L_i to the total life span mileage L, namely the probability $p(\sigma_{ei})$ of the equivalent stress amplitude σ_{ei} in the segment, the total damage D can be expressed as:

$$D = \frac{N}{C_1} \sum [\sigma_{ei}^m p(\sigma_{ei})] \tag{9}$$

When the number of segments is large enough, there is:

$$D = \frac{N}{C_1} \int [\sigma_{ei}^m p(\sigma_{ei})] d(\sigma_{ei}) \tag{10}$$

In order to obtain the equivalent stress amplitude that is closer to the actual situation, assume that the corrected constant amplitude σ and the amplitude of each segment σ_{ei} have caused the same damage within the whole life span, then there is:

$$\sigma = \sqrt[m]{\int [\sigma_{ei}^m p(\sigma_{ei})] d(\sigma_{ei})} \tag{11}$$

In the equation, the equivalent stress is a random variable, basing on its distribution randomness to conduct the damage analysis we can get more accurate conclusions. Under same working conditions, the equivalent stress amplitude usually fits normal distribution, compared with the mean value of the normal sample, the standard deviation of the distribution is generally ignored.

Combining with literature (Theodossiou, 1988) which studies the dynamic stress with minimum observation times based on t distribution theory and taking into full account of the characteristics of the tests, we select 10 tests under different working conditions within 1 month, and it is appropriate to use the mean value of its equivalent stress as the damage assessment standard under the recent typical working conditions of the frame.

4. Frame damage under different working conditions

According to the curvature-based working condition identification scheme from above passages, and taking into account the randomness of the dynamic stress test results, we analyzed the damage status of the train when it passes through curves of different radiuses and turnouts of different types in the depot and on the mainline.

4.1. Damage under mainline working condition

Table 2. Equivalent stress under mainline working condition(mpa).

Measuring points	Curve radius (km)			Straight line	Turnout type	
	5.5	7	10		12	18
1	15.7	14.9	14.6	14.3	30.2	24.7
2	7.2	6.6	6.8	6.6	22.5	17.3
3	10	9.5	8.8	9	19.1	16.8
4	20.1	17.7	15.3	14.9	34	28.9
5	20.4	17	15.5	14.7	33.7	29.4

The 350km/h high-speed railway line on which this train is running usually uses the No. 18 turnouts, and there may be some No. 12 turnouts when the regular-speed and high-speed mixed running stations are introduced. In principle, the minimum curve radius is 7000m, for particular difficult cases, the radius of the curve is 5500m. The radius of the most common regular curve in this test intersection is approximately 10000m. The data of the equivalent stress at the measuring points under some typical working conditions in the mainline application are now listed in the following table.

From the data in the table, it can be seen that the stress levels of the measuring points 4 and 5 near the weld of cross-beam and side-beam are higher, and the stress amplitude of the measuring point 2 at the small longitudinal-beam and the cross-beam weld is the lowest. As the radius of the curve rises, the equivalent stress level at each key point decreases to varying degrees. When the radius reaches about 10000m, the curve condition has no significant effect on the damage of the frame. When the EMU passes the turnouts, the stress amplitude is about twice that of the straight line. Compared with the No. 18 turnout, the 12th turnout's impact is even more obvious.

4.2. Damage under in-depot working condition

Due to factors such as the occupied area and the surrounding environment, the line conditions within the EMU section are usually quite complex. For the turnout types, besides single turnout, there are still equilateral turnout, double split turnout, the turnout type number is usually No. 9, sometime No. 12, most of which with a curve radius of 900m, in the design specification, it requires the curve radius in the sections should be ≥400m. In this test, there is a certain number of curves within a radius of about 500m. The following table shows the equivalent stress levels of the frame to-be-tested under several certain typical working conditions in the EMU sections:

Table 3. Equivalent stress under EMU depot working condition(mpa).

Measuring points	Curve radius (km)			Turnout type	
	0.5	0.9		9	12
1	25.3	21.4		68.1	42
2	14.8	9.9		44.5	29.1
3	15.2	13.1		41.3	33
4	31.6	24.5		73.9	39.6
5	28	25.7		78.2	47.5

It can be seen from the table that the stress levels and overall changes of the measuring points at different locations are similar to those under the mainline working condition. When the EMU passes through the No. 9 turnout in depot, the equivalent stress level reaches maximum. Even if the overall speed in the EMU section is limited to 30km/h, the equivalent stress at the key points will suddenly increase when the train passes through the turnouts and the small curves.

5. Conclusion

Basing on the curvature discriminant, this paper identifies the turnouts and curves with different radius in the depot or on the mainline during the operation of the EMU. In full consideration of the randomness of the equivalent stress distribution in the dynamic stress test, this paper extracts the frame stress data under typical operating conditions to conduct damage analysis, and the following conclusions are obtained:

During the mainline driving, the stress amplitudes of all the sample points increase when passing the curves, and the 4 and 5 measuring points at the connection of cross-beam and side-beam are particular obvious. The amplitude of each point when passing the turnouts is approximately 2 times of the straight-line working condition.

The situation inside the depot is even worse. Although the speed limit is only 1/10 of the mainline driving speed, the results show that the damage status of the frame is particularly sensitive to the radius of the curve and the type of the turnouts. Take passing through the No. 9 turnout in the depot at a low speed for example, the stress amplitude of the frame is approximately 5 times that of high-speed straight-line driving.

At the same time this paper proposes the equivalent stress correction scheme, it quantitatively gives damage degree of the bogie frame on some typical working sections. Start here, more in-depth research can be conducted to obtain damage data covering all types of frames under all operating conditions, which can provide theoretical basis for future refinement and design of bogies in different operating lines.

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