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On-line Monitoring of Railway Deformation Using Acceleration Measurement*

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***Abstract* - To ensure safety of railway operation, it is extremely important to regularly check railway conditions such as deformation of the rails. This paper presents an on-line rail deformation monitoring system for being implement on moving train so as to timely report any deformation beyond the threshold. The system is based an effective algorithm for detecting the rail deformation using three acceleration sensors mounted on the train. The proposed method can distinguish vibrations due to track deformation from those caused by motion of the train by analysing the lateral accelerations of the train's crossbeam and the lateral acceleration of the bogie. This method is testing on the railway between Shenyang and Dalian. Through experiment of large number of collected data, the performance of the detection is applicable.**

Index Terms - Acceleration, Multi-threshold, Vibration source decision, Railway deformation detection

I. INTRODUCTION

With the improving in train's speed and its transportation press, it is urgently needed a reliable and real-time system as an assistant to railway inspection.

There are a lot of methods to detect the railway deformation. Neural networks approach [3] is based on ultrasonic sensor to collect data. Digital Filtering Method [4] is one of the data processing methods and Rose, J.L., Avioli, M.J [5],[7] adopt guided wave performance for the railway detection.

Type ZT-3[2] train running aptitude instrument realizes the warning of the railway deformation by analysing the crossbeam's lateral and vertical acceleration, but it can't distinguish the vibration source. Type GJ-4[6] railway detection vehicle is a good-sized dynamic railway inspection instrument. Although GJ-4 detects the rails accurately, it is very expensive and uneasy to operate.

In this paper, we add an acceleration sensor mounted lateral on the train's bogie to collect the bogie's lateral acceleration, besides of crossbeam's lateral and vertical acceleration. Fig.1 shows the acceleration sensor and the sensor mounted vertical on the train's crossbeam. The arrowhead is pointed to the sensor.

Fig.1 Acceleration sensor: a) sensor module; b) sensor mounted vertically on the train's crossbeam.

The vibration acceleration straight reflects the stationarity of the running train, and it is the assessment index of the train running quality. We can recognize the train or railway's dynamic abnormity by the change of bogie's and crossbeam's acceleration.

Normally, the impact and vibration is stable when the train running, and its vibration acceleration's frequency and amplitude will wave in a fixed range.

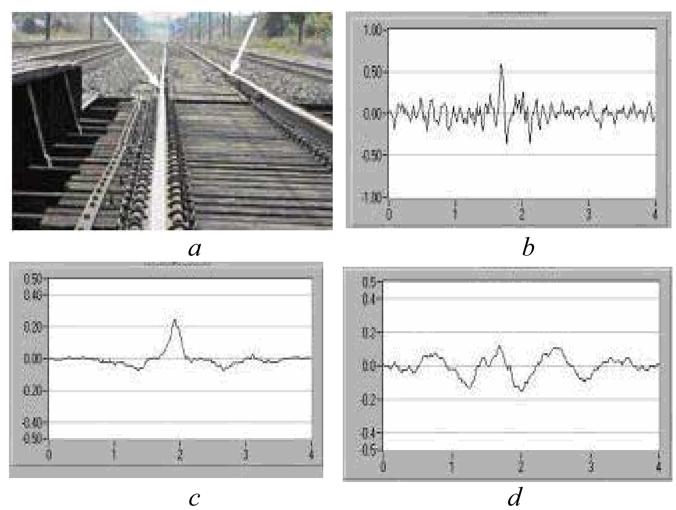

Fig.2 Railway deformation and its corresponding accelerations' waveforms: a) the deformation of the railway; b) the truck's lateral acceleration's waveform; c) the crossbeam's lateral acceleration's waveform; d) the crossbeam's vertical acceleration's waveform.

When railway is abnormal, the bogie's acceleration frequency and amplitude will change abruptly in advance, and then spread in a time, the crossbeam's lateral and vertical acceleration will also change. Fig.2 shows the deformation on the rail (pointed out by the arrowheads) and its corresponding accelerations' waveforms. When various train mounted

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monitoring sensor get across the abnormal position, their acceleration will have the same abrupt change, consequently we make decision that the railway is abnormal.

When train body is abnormal, the crossbeam's lateral and vertical acceleration will change at first, its frequency and amplitude wave continuously and unsteadily, then the bogie's acceleration will change or keep the same in a time, and the other train's monitoring sensor will don't take the same change, accordingly we determine the train is abnormal.

In this paper, we present a method of multi-threshold feature extraction for railway deformation detection, and simply discuss the vibration source decision flow.

Notice: in this paper the crossbeam's lateral and vertical acceleration are the vibration acceleration collected by the acceleration sensor mounted lateral and vertical on the train's crossbeam, and lateral on the train's bogie. The vibration source in this paper is train's body or the railway.

II. The On-Line Monitoring System of Railway Deformation

The principle of the on-line monitoring system of railway deformation is: collecting the train running data information and pretreating the vibration acceleration through vehicle carried system, then sending the data information to the data processing station by CDMA(Code Division Multiple Access) module on real-time, and the data processing station deal with the received data and achieve the railway's quality information, and at the same time the station sending out the results to the railway station for the loco man's servicing. Fig.3 shows the schematic of this system.

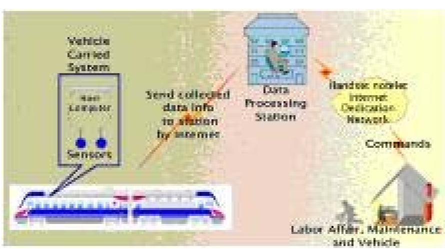

Fig.3 The schematic of the on-line monitoring system of railway deformation

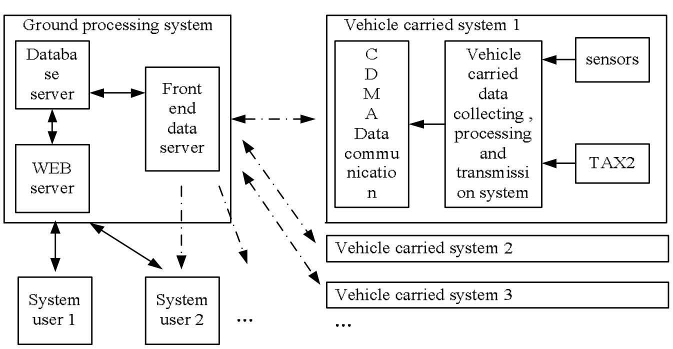

Fig.4 Construct of on-line monitoring system

The on-line monitoring system [1] is constituted by locomotive vehicle carried system and ground data processing system. We can see in Fig.4. Fig.4 shows the vehicle carried system is constructed by CDMA data communication module, vehicle carried data collecting, data processing and data transmission system, the acceleration sensors and the TAX2(integrated detection system for locomotive security info of TAX2 type). The ground processing system is constructed by data server, WEB server and front end data server. And the system user is just the railway department.

III. Deformation Detection Based on Multi-Threshold Feature Extraction

A. The Set of Feature Extraction Threshold

We adopt five thresholds to extract the acceleration's feature. So we have to set the threshold of crossbeam's lateral and vertical acceleration and bogie's lateral acceleration differently. We can see in Table I.

For the convenience of describing, we employ some defines:

Plus mean: $\forall$ sequence Xn, calculate the number of the data which greater than zero, and calculate their mean value, we define it as plus mean.

Plus variance: $\forall$ sequence Xn, calculate the number of the data which greater than zero, and calculate their variance, we define it as plus variance.

Calculate the threshold of the bogie's lateral acceleration Ax_2 : $Ax_2 = \{ zx_1, zx_2, zx_3, \ldots, zx_n \}$ (known), suppose the plus mean of Ax_2 is mean_plus, the plus variance of Ax_2 is va_plus, the num of data which greater than zero in Ax_2 is m, then we get the follow equations.

$$mean\_plus = \frac{1}{m}\sum_{i=1}^{i=n} zx_i \qquad (zx_i > 0). \tag{1}$$

$$va\_plus = \sqrt{\frac{\sum_{i=1}^{i=n}(zx_i - mean\_plus)^2}{m}} \qquad (zx_i > 0). \tag{2}$$

$$gate_i = mean\_plus + a_i * va\_plus \quad (i = 1,2,3,4,5). \tag{3}$$

(Coefficient: $a_1 = 0.8,\ a_2 = 1.2,\ a_3 = 1.6,\ a_4 = 2.2,\ a_5 = 2.8.$)

TABLE I
FEATURE EXTRACTION THRESHOLD

Crossbeam's vertical acceleration feature extraction threshold	$gate_1, gate_2, gate_3, gate_4, gate_5$. (known)
Crossbeam's lateral acceleration feature extraction threshold	$gate_1, gate_2, gate_3, gate_4, gate_5$.(known)
Bogie's lateral acceleration feature extraction threshold	$gate_1, gate_2, gate_3, gate_4, gate_5$.(unknown)

B. The Principle of Multi-Threshold Weight Coefficient Comparison Method

We known $Ax_1 = \{ ax_1, ax_2, ax_3, \ldots, ax_n \}$(n=30000) is the crossbeam's lateral acceleration in one minute, we have to calculate its feature value $Chara\_Ax_1 = \{ chara\_ax_1, chara\_ax_2, chara\_ax_3, \ldots, chara\_ax_n \}$.

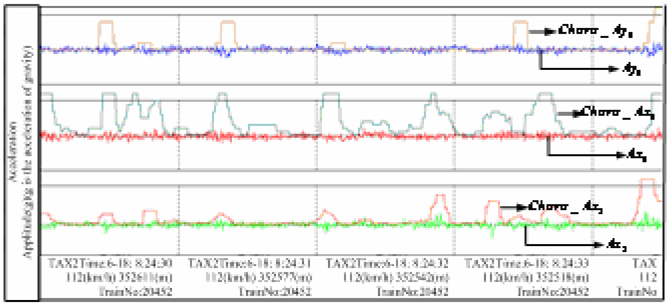

Fig.5 Accelerations and features' waveforms

Suppose the feature extraction's frame length is L_1, and step length is L_2, and $gate_1 < gate_2 < gate_3 < gate_4 < gate_5$. We use $num_1, num_2, num_3, num_4, num_5$ to take count of the data greater than the threshold in the range of L_1. In which the num_1 take count of the acceleration greater than $gate_1$ but smaller than $gate_2$, the num_2 take count of the acceleration greater than $gate_2$ but smaller than $gate_3$, and by the same way we can gain the num_3, num_4 and num_5.

Take the acceleration from ax_{1+i*L_2} to $ax_{1+i*L_2+L_1}$ ($0 \le i \le n/L_1$), compare with the five threshold, then we gained num_1, num_2, num_3, num_4 and num_5. A simple equation as follow gains the value $Chara\_Ax_1$:

$$Chara\_Ax_1[j] = 0.1*num_1 + 0.2*num_2 + 0.4*num_3 + 0.6*num_4 + 0.9*num_5 \quad (i*L_2<j<i*n/L_2). \tag{4}$$

In a similar way we can gain the crossbeam's vertical acceleration's feature value $Chara\_Ay_1$ and the bogie's lateral acceleration's feature value $Chara\_Ax_2$.

According to the train wheel's diameter is about 1 meter and the sampling frequency is 500Hz, and suppose the average speed of the train is 30(m/s), we decide the frame length and step length: L_1=50, L_2=10.

Fig.5 shows the feature extraction result. Fig.5 in the three frames the above curves are the features' waveforms, and the below curves are the accelerations' waveforms. We can see that the feature's waveform gives direct-view of the acceleration's wave and it is more convenient to detect railway deformation.

C. Vibration Source Decision Flow Graph

Fig.6 shows the vibration source decision flow. In Fig.6 source==1 means undetermined, source==2 means railway deformation is the vibration source, and source==3 means the vibration source is the train's body. The vibration source decision detail is introduced in [8].

D. Railway Deformation Detection Flow

Through multi-threshold weight coefficient comparison method, we gain the feature value $Chara\_Ax_1$, $Chara\_Ax_2$ and $Chara\_Ay_1$ of Ax_1, Ax_2 and Ay_1. Then we have to determine the judge threshold of $Chara\_Ax_1$, $Chara\_Ax_2$ and $Chara\_Ay_1$.

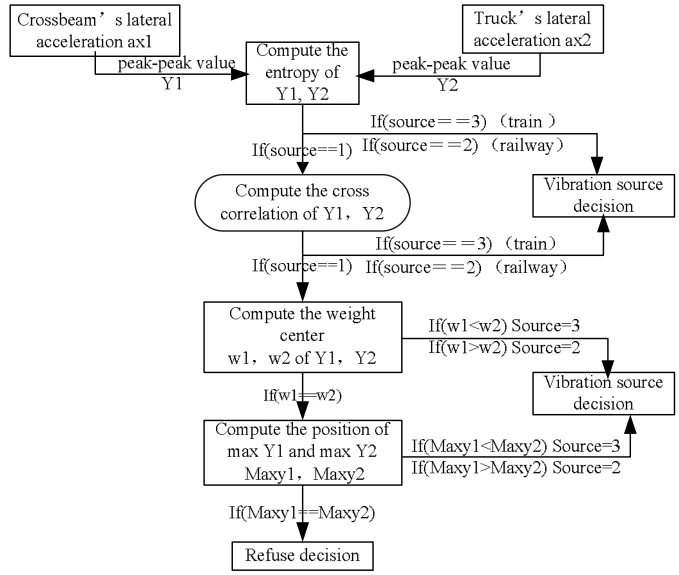

Fig.6 Vibration source decision flow graph

The judge threshold $Ay_1\_threshold$, $Ax_1\_threshold$ and $Ax_2\_threshold$ can tune by users. The tuneable parameters $Ay_1\_a_1$, Ay_1_belt, $Ax_1\_a_2$, Ax_1_belt and $Ax_2\_a_3$ separately are the tuneable parameters of $Ay_1\_threshold$, $Chara\_Ay_1$'s bandwidth, $Ax_1\_threshold$, $Chara\_Ax_1$'s bandwidth and $Ax_2\_threshold$. The expression of the three amplitude threshold equations is as follows.

$$Ay_1\_threshold = 0.31 + Ay_1\_a_1 * Ay_1\_\mathrm{var}. \tag{5}$$

$$Ax_1\_threshold = 0.25 + Ax_1\_a_2 * Ax_1\_\mathrm{var}. \tag{6}$$

$$Ax_2\_threshold = 0.64 + Ax_2\_a_3 * Ax_2\_\mathrm{var}. \tag{7}$$

(Ay_1_var, Ax_1_var, Ax_2_var are the variances of $Chara\_Ay_1$, $Chara\_Ax_1$, $Chara\_Ax_2$.)

Because $Chara\_Ax_1$ and $Chara\_Ay_1$ both are crossbeam acceleration's feature, we need to compare $Chara\_Ax_1$ with $Ax_1\_threshold$ and $Chara\_Ay_1$ with $Ay_1\_threshold$ at the same position. $Chara\_Ax_2$ is the bogie's acceleration's feature, the bogie is nearer to railway than crossbeam, so we need to compare $Chara\_Ax_2$ with $Ax_2\_threshold$ at the position a little forward.

Fig.7 shows the decision flow of possible deformation.

There will be bridges, curves and turnouts when the train running and the vibration acceleration is great as the train gets across the turnout, so we not only have to determine the vibration source but also have to exclude the turnout influence.

Fig.8 shows the flow graph of railway deformation detection after vibration source decision, and eliminates the turnout by enquiring the database.

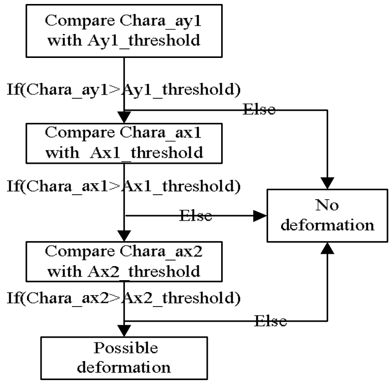

Fig.7 The decision flow graph of possible deformation

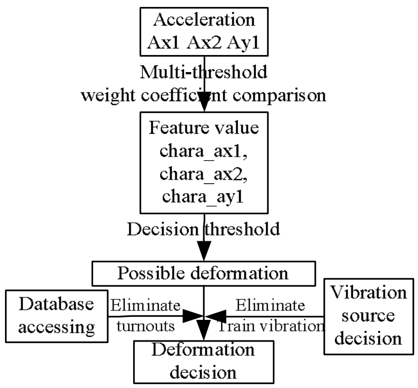

Fig.8 Railway deformation detection flow graph

IV EXPERIMENTAL RESULTS

In this paper we divide the deformation into three classes: large deformation, mid-deformation and small deformation.

Large deformation: the deformation is very dangerous for the train running and it needs to eliminate urgently. The value of $Chara\_Ax_1$, $Chara\_Ax_2$ and $Chara\_Ay_1$ are all great, $Chara\_Ax_1$'s and $Chara\_Ay_1$'s bandwidth are wide.

Mid-deformation: the deformation is not so dangerous as the large deformation but also need to eliminate. The value of $Chara\_Ax_1$, $Chara\_Ax_2$ and $Chara\_Ay_1$ are on the high side, $Chara\_Ax_1$'s and $Chara\_Ay_1$'s bandwidth are on the wide side.

Small deformation: the deformation is a latent danger to train running, it is indistinct and we can eliminate it later. The value of $Chara\_Ax_1$, $Chara\_Ax_2$ and $Chara\_Ay_1$ are a little great, $Chara\_Ax_1$'s and $Chara\_Ay_1$'s bandwidth are a little wide.

Set the small deformation decision threshold parameter:

$$Ax_1\_a_2=0.2,\ Ay_1\_a_1=0.2,\ Ax_2\_a_3=0.2,\ Ax_1\_belt=55,\ Ay_1\_belt=50. \tag{8}$$

Set the mid-deformation decision threshold parameter:

$$Ax_1\_a_2=0.5,\ Ay_1\_a_1=0.5,\ Ax_2\_a_3=0.5,\ Ax_1\_belt=100,\ Ay_1\_belt=90. \tag{9}$$

Set the large deformation decision threshold parameter:

$$Ax_1\_a_2=1.0,\ Ay_1\_a_1=1.0,\ Ax_2\_a_3=1.2,\ Ax_1\_belt=220,\ Ay_1\_belt=200. \tag{10}$$

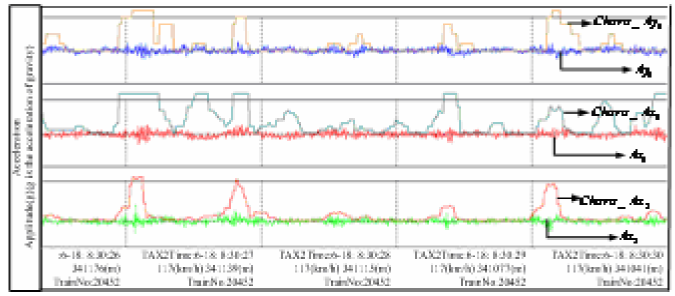
Fig.9 The feature extraction graph

The data is collected at different position and with different train running on the railway between Shenyang and Dalian.

Fig.9 shows the first step of deformation decision.

Fig.9 in the first frame: the below curve is the crossbeam's vertical acceleration waveform; the above curve is the corresponding feature waveform. In the second frame: the below curve is the crossbeam's lateral acceleration waveform, the above curve is the corresponding feature waveform. In the third frame: the below curve is the bogie's lateral acceleration waveform, the above curve is the corresponding feature waveform. And the characters tell us the milestone, time, speed, section, turnout and curve information, the turnout information we label in the fourth line, and in this milestone there is no turnout.

According to the feature waveform, first we set the large deformation decision threshold parameters shown in (10). And the result reveals that there is no large deformation. We can see in Fig.10.

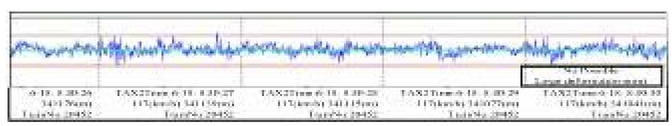
Fig.10 The position of possible large deformation graph

Second we set the mid-deformation decision threshold parameters shown in (9). And we get the position of the mid-deformation. See in Fig.11.

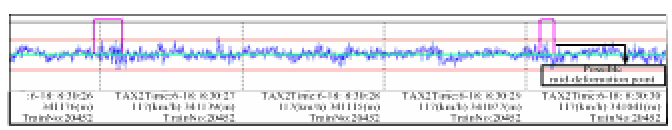
Fig.11 The position of possible mid-deformation graph

Fig.11 the above curve reveals the position of possible mid-deformation.

At last we set the small deformation decision threshold parameters show in (8). And we get the position of possible deformation. See in Fig.12.

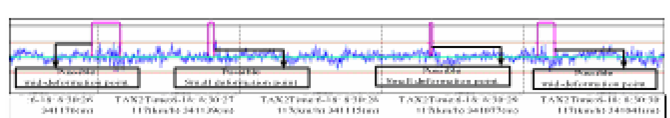
Fig.12 Position of possible deformation graph

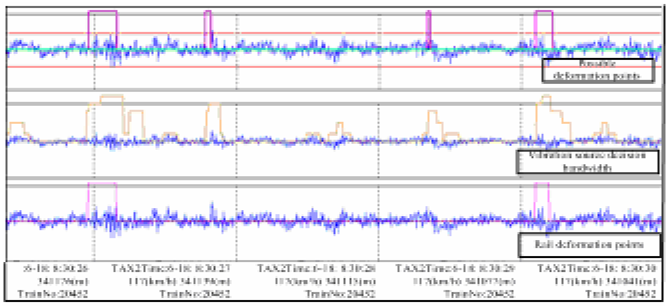

Fig.13 Vibration source decision step graph

Fig.12 the above curve reveals the position of possible deformation, and the two labels in the middle are the possible small deformation, others are the possible mid-deformation.

In this paper we set the crossbeam's vertical acceleration feature bandwidth of the possible deformation position as the vibration source decision's frame length. We can see the step in Fig.13.

Fig.13 shows the step of vibration source decision. In the first frame: the above curve reveals the position of possible deformation. The second frame: the above curve reveals the bandwidth of the crossbeam's vertical acceleration feature. And the third frame: the above curve reveals the position of the railway deformation vibration source, at the bottom is the milestone, time and speed information etc. Combine with fig.12 we get the position of mid-deformation is 341.139(km) and 341.041(km) and there is no large deformation and small deformation.

Fig.14 shows the acceleration and its feature waveform when the train passes the turnout as shows in Fig.15 [9].

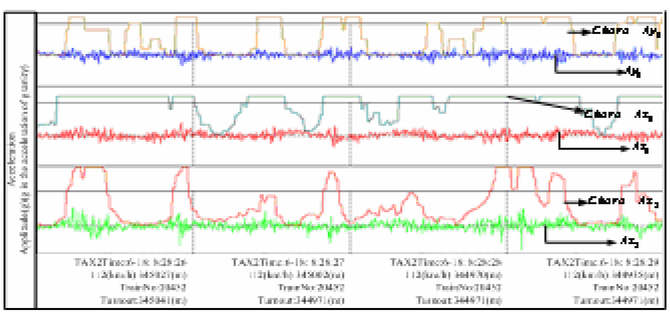
Fig.14 The accelerations and features' waveforms when pass the turnout

TABLE II

THE RESULTS OF TESTING FOR THE SYSTEM

Labelled deformation points	316
System detects points	261
The detection rate	82.86%


Fig.15 The turnout

Fig.14 the fourth line word labels the turnout information, and in this section the position of the turnout are 345.041(km) and 344.971(km). We can see that the amplitude of acceleration and feature are all on the high side. So we need to eliminate it while progressing deformation detection, namely if the possible deformation is the turnout, we determine it is not the deformation.

We have tested on the system, see in Table II.

V. CONCLUSION

In this paper, the experiment reveals that the method is in high efficiency, comparing with the ZT-3 it can decide the vibration source; and comparing with the GJ-4 it is more simple and convenient. The interface of the experiment is also very simple and convenient, and the result of the experiment displayed very visually.

Regardless of the attractive performance of the detection method, there are some issues to be researched: the vibration source decision complexity, the detection rate and threshold setting. We need to improve on them while the system testing on the railway between Shenyang and Dalian.

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