Analysis of Electromagnetic Force and Vibration caused by Passing Maglev Train on Guideway Switch

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ABSTRACT: 3-phase stator windings and feeder cables are arranged on the steel guideway switch. When a maglev train passes the switch, current of up to 2000 A flows in the cables and the interaction of the electromagnetic forces among these cables cause the feeder cables to vibrate. This vibration is likely to be amplified when it is transferred to the steel guideway switch, thus bringing about adverse effect on the switch. This paper conducts a calculation of the electromagnetic forces of the feeder cables and detailed measurement of the vibration of the switch. The analytical results and the suggestion to the arrangement of the feeder cables on the switch are presented.

1 INTRODUCTION

It has been three years since Shanghai Maglev Line began its commercial operation. The efficient and reliable running proves that Transrapid Maglev Technology is mature enough to fulfill the commercial requirement. However, during the daily work beside the track we found that the design of some components, for example the guideway switches, still have some deficiency need to be improved.

There are eight guideway switches on Shanghai Maglev Line, four of which is near the Long Yang Road Station (LYR Station), two near Pudong International Airport Station (PIA Station), one in Maintenance Area, and one at the intersection of main line and the branch line to Maintenance Area.

During the normal running, some abnormal vibration and corresponding noise could be observed when the vehicle is near the guideway switch but not on it. It is seems that this kind of vibration is related to the stator current that flow in the 3-phase stator windings and feeder cables. When the vehicle near the guideway switches, the amplitude of the stator current could reach 2000A or more, which lead to electromagnetic forces between the 3-phase feeder cables that big enough to make the cables vibrate in the cable box and excite the guideway switches, bringing some adverse effect on the safety running.

This paper describes the abnormal vibration, presents the test result, and draws a conclusion of the real reason for the vibration. Additionally, the value of the electromagnetic forces is calculated roughly, and finally some effective advice is proposed to restrain and reduce the vibration.

2 THE ABNORMAL VIBRATION OF THE GUIDEWAY SWITCHES

In this paper, the vibration of the guideway switch when the vehicle passing by it is defined as **load vibration**, and the vibration when the vehicle is not on it calls **abnormal vibration**.

The behavior of the abnormal vibration is that: when the vehicle just start from the platform, a distinct vibration noise is heard around the guideway switches that near the station until the vehicle passes by; and when the vehicle decelerate and nearly stop at the platform, the noise also could be heard around the switches area. The sound is consists of two parts. One is the linear motor electromagnetic noise whose frequency varies along with vehicle velocity, and another is mechanical noise caused by some components of the guideway switch.

There are several possible reasons causing the vibration as follow:

- The moving vehicle excites the guideway girders under it causing the vibration which transmits to the guideway switches through the girders and columns. When the exciting frequency accord with the nature frequency of the guideway switch, the vibration is magnified and produces the noise.
- The moving vehicle excites the power rail mounted on the girder causing the vibration which transmits to the guideway switches and bring the noise.
- The power cables (including stator cables and feeder cables) on the guideway switches vibrate by the electromagnetic forces produced by the stator current, which causes the abnormal vibration.
- The electronic cables in the cable box under the

guideway switches vibrate and causing the noise.

Since there is no physical connection between the guideway switches and the girders under the vehicle except the stator winding, the first possibility mentioned above could be ignored. Other hypothesizes should be approved by vibration tests.

3 VIBRATION TEST

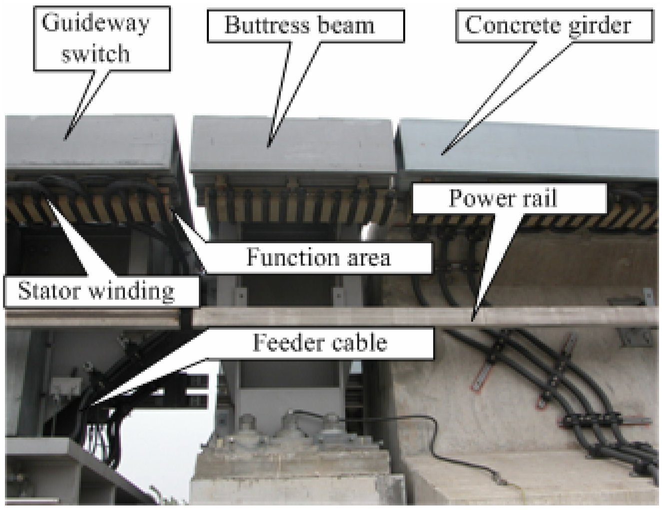


Figure 1: Picture of the guideway switch on Shanghai Maglev Line

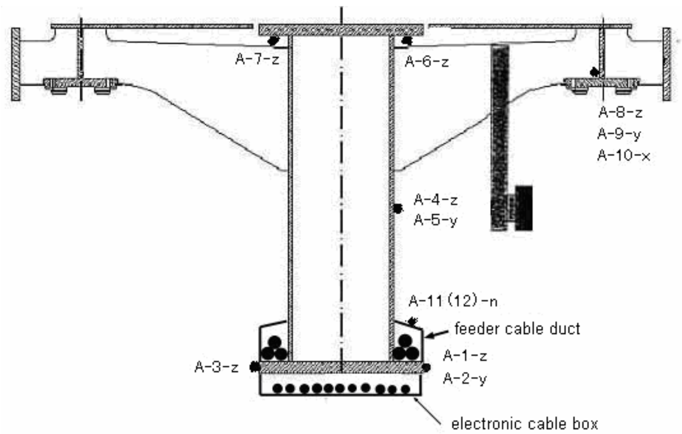
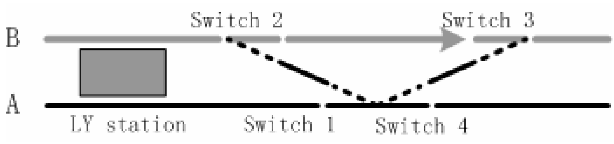


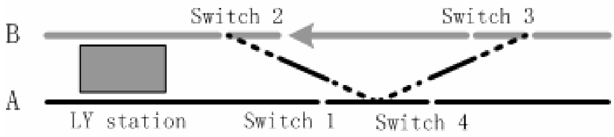
Figure 2: Test positions layout on the guideway switch

Table 1: Explanation for the test positions

No.	Chanel name	Position	Note
1	A-1-z	Mid-span between support 2 and support 3	Presenting the vibration of the bottom flange of Switch 3
2	A-2-y		
3	A-3-z		
4	A-4-z		Presenting the vibration of the web plate of Switch 3
5	A-5-y		
6	A-6-z		Presenting the vibration of the up flange of Switch 3
7	A-7-z		
8	A-8-z		Presenting the vibration of the function area of Switch 3
9	A-9-y		
10	A-10-x		
11	A-11-n	Near the support 2	Presenting the vibration of the cover of the cable duct of Switch 3
12	A-12-n	Mid-span between support 2 and support 3	



(a) Mode 1



(b) Mode 2

Figure 3: Vehicle running modes

We conduct a series of tests, in which acceleration sensors are mounted at the doubtful exciting positions at the switch, and the exact exciting point could be found by the acceleration signal acquired.

The test result shows that there is no distinct vibration signal detected by the sensors at the power rails, functional areas (in which the stator windings are mounted), and electronic cable box when the abnormal vibration happens. As a result, the vibration is closely related to the feeder cables that mounted on the bottom flange of the switch. We use one of the significant test results as a example to explain the real reason of the vibration.

Due to the limit of the paper length, only the results of the most intensive vibrating positions are referred in this paper, which are shown in Figure 4 and Figure 5.

Figure 1 shows the guideway switch of Shanghai Maglev Line. The test positions layout is shown in Figure 2[(1)], in which the horizontal direction is named y-direction, vertical named z-direction, perpendicular to the paper named x-direction, and n-direction means the direction perpendicular to the plane the sensor mounted. The explanation of these positions is listed in Table 1, and the train running modes for the test is given in Figure 3: Vehicle running modes. Figure 1, 2, 3 and 4 in Figure 3: Vehicle running modes are switch numbers, and the train running direction are presented by the arrowhead of the gray thick line, besides the gray rectangle means the platform of LY Station. All positions are located at the mid-span of the support 2 and support 3 of the Switch 3 except A-11-n, which is on the section of support 2.

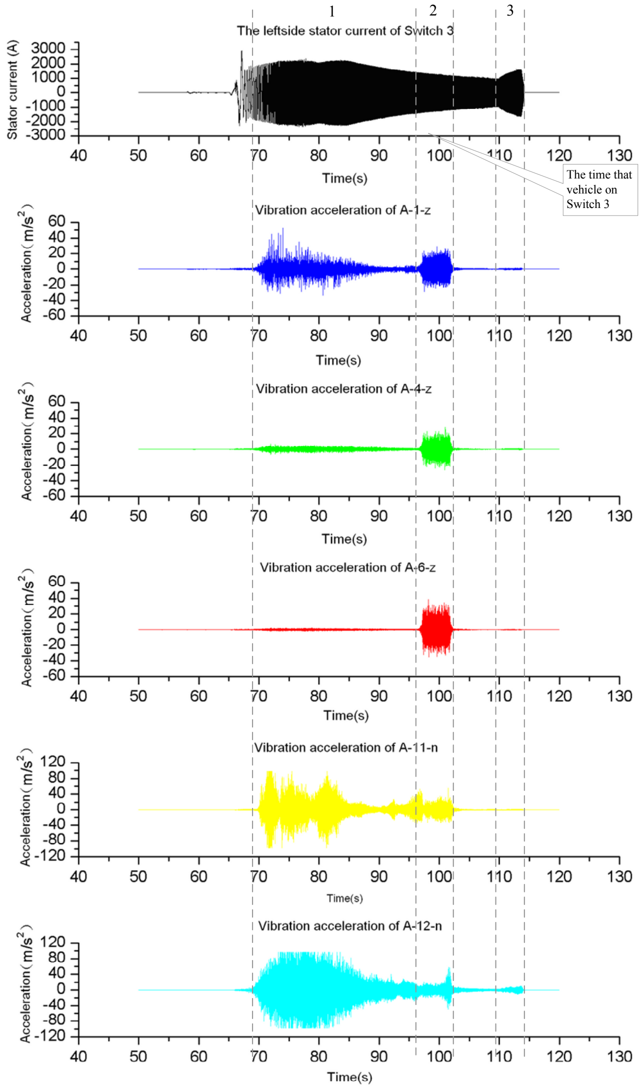


Figure 4: Running mode 1: Acceleration of the upper flange, middle and bottom flange of the bending beam

In light of the test results, it seems that the abnormal vibration is closely related to the amplitude of the stator current. For example, in Figure 4 the time section 1 means the interval between the vehicle starting and before its reaching Switch 3. To obtain as much as large thrust for the vehicle, the amplitude of the stator current is very high during this time, about 2000A or more. Accordingly, apparent vibration acceleration signals could be observed at position A-1-z, A-11-n and A-12-n in section 1. Similarly in Figure 5, distinct vibration signals also could be seen at position A-1-z, A-11-n and A-12-n in section 1 and 3, during which the amplitude of the stator current is higher than 1500 A correspondingly.

It also could be found that the abnormal vibration is a kind of local vibration. In Figure 4 and Figure 5, the most intensively vibrating position is A-12-n, and then A-11-n. A-1-z also vibrates obviously, but its acceleration amplitude is apparently less than A-12-n. Position A-4-z and A-6-z vibrate more weakly with their distance from the feeder cable duct longer. Moreover, no explicit signal could be seen at position A-8-z, A-9-y and A-10-x (not shown in this paper). Therefore, it could be confirmed that the excitation source of the guideway switch abnormal vibration is near the feeder cable ducts.

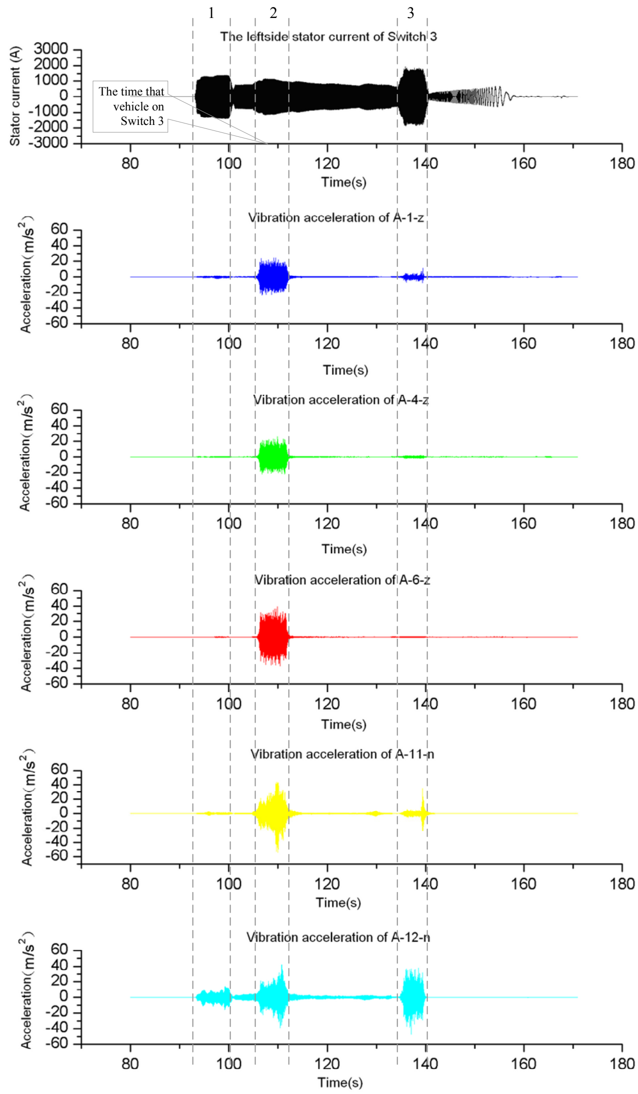


Figure 5: Running mode 2: Acceleration of the upper flange, middle and bottom flange of the bending beam

In the spectrum (not shown in this paper) of the acceleration data, no characteristic frequency could be found, and the relationship between the stator current frequency and that of the vibration acceleration also could not be observed. Integrating the acceleration data of point A-1-z, the displacement of A-1-z during vibration is calculated, and the result shows that the order of the displacement is 10^{-2} mm.

Based on the above analysis, the abnormal vibration of guideway switch is due to the feeder cables mounted in the cable ducts on the bottom of the switches. The cover of the ducts (on which poison A-11-n and A-12-n is located) are not integrated with the switch but fixed on it by screws. Although the feeder cables are arranged in the ducts as shown in Figure 6, they are not enlaced effectively. When the large stator current feeds into the cables, the electromagnetic forces are induced, attracting and repulsing the cables and making them knock the switch and the covers, producing noise.

The abnormal vibration is still in the safety range. However, long term vibration will shorten the life of the components and put adverse effect on the reliability of the switch. As a result, it is necessary to take some measures to restrain or eliminate this abnormal vibration.

4 CALCULATION OF THE ELECTROMAGNETIC FORCES

To quantify the vibration excitation, the electromagnetic force that acts on the feeder cable in the cable box of the guideway switch is analyzed as bellow. The three-phase feeder cables are arranged as shown in Figure 6. The three-phase stator current is represented in formula 1~3, in which I_m is 2000 Amp during calculation.

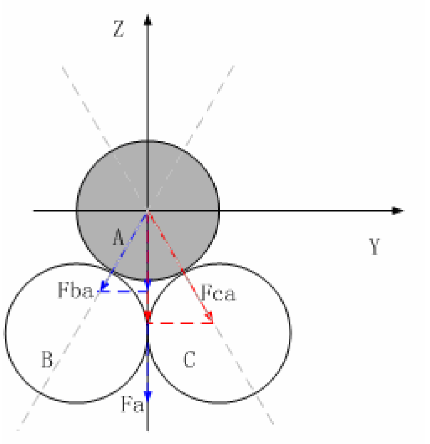


Figure 6: The forces act on feeder cable phase A

$$i_A = I_m \cos \varpi t \qquad (1)$$

$$i_B = I_m \cos(\varpi t - 120^o) \qquad (2)$$

$$i_C = I_m \cos(\varpi t - 240^o) \qquad (3)$$

So the force between two parallel conductors could be expressed as follow(2):

$$F = \frac{\mu_0 i_1 i_2}{2\pi S} = \frac{\mu_0}{2\pi} \times \frac{i_1 i_2}{S} = C \frac{i_1 i_2}{S} \qquad (4)$$

in which，

$$C = \frac{4\pi \times 10^{-7}}{2\pi} = 2 \times 10^{-7} N / A^2$$

The electromagnetic forces between 3 phase feeder cables are shown in Table 2. Apparently although the value per meter is not very high, it is large enough to produce vibration and noise.

Table 2: Electromagnetic forces calculation results

Direc.	Phase A Mag. Force (N/m)	Phase A ϖt	Phase B Mag. Force (N/m)	Phase B ϖt	Phase C Mag. Force (N/m)	Phase C ϖt
Max. of z	18	0°	-13.3	150°	-13.3	150°
Max. of y	-8.9	45°	-21.7	105°	21.7	105°

5 SOLUTIONS

To eliminate abnormal vibration, the arrangement of the feeder cables on guideway switches need to be redesigned, to the most extent avoiding the influence of electromagnetic forces. As far as the switches on Shanghai Maglev Line are concerned, two measures were taken to restrain the feeder cable vibration as following:

- Closely enlace the 3-phase cables like what is shown in Figure 6, so as to eliminate the effect of the magnetic fields induced by 3-phase current, and then reduce the influence of the magnetic fields on the circumstance around the cables.
- To the most extent integrate the cables with guideway switches to restrict the moving of feeder cables. For example, fill the space between the cables and switches, and cables and the ferrous cover of cable ducts with insulated rubber.

Another test was performed after the two measures were taken. The results shows that the amplitudes of acceleration of point A-1 (3)-z and A-11 (12)-n are reduced 70~80 %.

6 CONCLUSIONS

The conclusions are as follow:

- The abnormal vibration is due to the electromagnetic forces of the feeder cables.
- To get rid of abnormal vibration, it is needed to change the current arrangement of feeder cables on guideway switches.
- The vibration could be effectively restrained by some measures such as close enlacement and filling with damping material and so on.

7 REFERENCES

(1) Gert Schwindt and Peter-Jürgen Gaede. The Bending Switch. *Proc. of Int. Conf. on Magnetically levitated system'88, 1988.*

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