Effect of vertical vibration on the stability of Side-Suspending HTS Maglev Rotating System with trimodal structure PMG

To cite this article: Li-Feng Zhao et al 2018 J. Phys.: Conf. Ser. 1054 012089

View the article online for updates and enhancements.

Related content
- Side-suspended High-Tc Superconducting Maglev Prototype Vehicle Running at a High Speed in an Evacuated Circular Test Track
  Dajin Zhou, Lifeng Zhao, Chenyu Cui et al.
- Vibration analysis of continuous maglev guideways with a moving distributed load model
  N G Teng and B P Qiao
- Vertical vibration of elevator compensating sheave due to brake activation of traction machine
  S Watanabe and T Okawa
Effect of vertical vibration on the stability of Side-Suspending HTS Maglev Rotating System with trimodal structure PMG

Li-Feng Zhao¹,², Meng-Liang Yao¹,², Lin-Bo Li¹,², Xifeng Pan³, Da-Jin Zhou¹,², Jing Jiang¹,², Yong Zhang¹,² and Yong Zhao¹,²

¹Key Laboratory of Magnetic Suspension Technology and Maglev Vehicle, Ministry of Education, Chengdu, 610031, China.
²Superconductivity and New Energy R&D Center, Southwest Jiaotong University, Chengdu 610031, China,
³National Engineering Laboratory for Superconducting Materials (NELSM), Western Superconducting Technologies Company, Ltd. (WST), Xi’an 710018, China.

zhaolf@home.swjtu.edu.cn

Abstract. By changing the vibration amplitude, side-suspending gap and load of side-suspending maglev system, respectively, the influence of vertical vibration on the bearing stability of the side-suspending high temperature superconducting (HTS) maglev system with trimodal structure permanent magnetic guideway (PMG) is investigated. The results show that the attenuation of the side-suspending height increases with the increase of the vibration amplitude, side-suspending gap and load, respectively. However, the overall decrease of the side-suspending height is not larger than 1.5 mm under all situations, and it will not affect the stability of the side-suspending maglev system apparently.

1. Introduction
The Meisner effect and flux pinning characteristics of HTS bulk make it possible to form a self-stabilizing system suspending over a permanent magnet without additional energy consumption [1, 2]. This characteristic has potential application prospects on flywheel energy storage [3], vacuum pipeline maglev train and so on [4, 5]. The vacuum pipeline maglev system is safe and energy-efficient because it avoids air-resistance and mechanical friction resistance. It is thus regarded as the ultimate solution for the future transportation. The future vacuum pipeline for maglev system is most likely laid on viaduct. The periodic flexure deformation of viaduct will form a low-frequency vibration source for
maglev train running at high-speed. Earlier reports point out that low-frequency vibration will cause the levitation force of HTS maglev system to decrease [6, 7]. In order to study the dynamics of the maglev system running in an evacuated pipeline, a side-suspending maglev system running along a circular PMG with the diameter of 6.5 m in a vacuum pipeline has been built recently in the Superconductivity and New Energy R&D Center of Southwest Jiaotong University, China. It can reach the speed of 150km/h, and it is the fastest HTS maglev system running in the vacuum pipeline [8-10]. However, further studies show that the two unimodal structure PMGs (UMGs) of the system can be combined into a single trimodal structure PMG (TMG), which can obviously improve the running speed of side-suspending maglev system [11].

In view of the side-suspending maglev system running along the circular TMG in the evacuated pipeline, and in order to further study the effect of periodic low-frequency vibration on the safety of maglev train, this paper discusses the influence of low-frequency vertical vibration on the bearing stability of the side-suspending maglev system.

2. Experiments

The cross section diagram of the side-suspending HTS maglev rotating system with two UMGs is shown in figure 1. a. The every block with an arrow inside is the permanent magnet with the section size of 40 mm×40 mm. The arrow stands for the direction of the magnetic field for each block. The black portion represents iron with the section size of 6 mm×40 mm, the iron between two permanent magnets provides a peak of magnetic field nearby. The improved PMG structure is just to put the two UMGs together to form a single TMG, as shown in figure 1. b. As there is an additional magnetic peak formed, the TMG can provide greater centripetal levitation force when the maglev vehicle runs along the circular TMG. This improvement can obviously increase the running speed of the side-suspending maglev rotating system without changing the system structure greatly.

Due to the installation error of the circular TMG in the vacuum pipeline, the side-suspended maglev system will be subject to low-frequency vibrations in both vertical and radial directions when it's running along the TMG. The effect of the radial vibration on the centripetal levitation force for the system is equivalent to the influence of the alternating field on the levitation force for the traditional maglev mode of a HTS bulk suspending over a permanent magnet, and it has been much discussed [12]. However, for the side-suspending system in this paper, the effect of vertical vibration on the carrying capacity of the side-suspending system perhaps decreases the stability of the system. Therefore, we design the vibration test device, as shown in Fig. 2, to evaluate the effect of low-frequency vibration in the vertical direction on the carrying stability of the side-suspending maglev system. In Fig. 2, the section size of TMG is the same as that in Fig. 2. b with the length of 350 mm. The cryostat's outer size is 35 mm×150 mm×90 mm.

The test device is consisted of a vibrator, a TMG fixed with the vibrator, 6 HTS bulks fixed in a cryostat and two laser displacement sensors. Magnetic components of $B_x$ and $B_z$ at the height of 10mm over the TMG surface are presented in figure 3.

The experiment is designed to evaluate the dynamic stability of the side-suspending system under vibration with different amplitude, side-suspension gap and load of the vehicle. The experimental conditions are set as follows, respectively. a) The effect of vibration amplitude: the side-suspending gap was set as 10 mm, and the vibration amplitude of the vibration source was set as 1, 2, 3, 4 mm,
respectively. b) The effect of different side-suspending gap: the vibration amplitude was set as 3mm, and the side-suspending gap was set as 5, 8, 10, 13, 15 mm, respectively. c) The effect of different maglev loads: the vibration amplitude was set as 3 mm, and the side-suspending gap was 10 mm, the extra load for the maglev vehicle was 0, 125, 250, 375 and 500g, respectively. After the experimental conditions had been set up, the liquid nitrogen was fulfilled into the cryostat to make the HTS bulks achieve superconducting state and keep 10 minutes, then laser displacement sensors were used to record the primary side-suspending height of cryostat (H₀) and displacement variations of the TMG and cryostat in the vertical direction caused by vibration, respectively.

When the maglev vehicle was accelerated from standstill to cruising speed along the circular TMG, HTS bulks experienced the alternating magnetic field caused by the installation error of TMG and the frequency of it increased gradually. Therefore, in this experiment, the vibration frequency was set to increase from 0 to 20 Hz in 5 minutes and further keep the frequency of 20 Hz for 5 minutes, and then the final side-suspending height of cryostat (Hᵥ) could be obtained when the vibration device was closed. Thus H₀-Hᵥ represents the attenuation of side-suspending height.

![Figure 1](image1.jpg)

**Figure 1.** Cross-sectional structure of the side-suspended maglev system in the evacuated tube. (a) Established maglev system possessing two parallel UMGs; (b) The maglev system with one TMG; (1) Linear motor. (2) Iron. (3) Liquid nitrogen container. (4) HTS bulk. (5) Vacuum tube.

![Figure 2](image2.jpg)

**Figure 2.** Schematic diagram of the vibration test device. The cross-section size of TMG is 40mm × 190mm, and the length of it is 350 mm. The outer size of cryostat is 35 mm × 150 mm × 90 mm.
3. Results and discussion

A typical time-domain vibration response of the cryostat with the TMG at the gap of 10 mm and the vibrator source amplitude of 2 mm is shown in figure 4. In figure 4, when the vibrator starts to work, frequency of it is increased from 0 to 20 Hz in 300 s. In order to observe the attenuation of amplitude of cryostat with time under the frequency of 20 Hz, it has been kept for 15 minutes. With the increase of frequency, the amplitudes of cryostat and TMG decrease rapidly. This should be accord with the situation of the side-suspending maglev running along the TMG, for the reason that higher speed means higher frequency, and Mass inertia of maglev vehicle leads to smaller amplitude at the same time. Furthermore we can also figure out in figure 4 that the side-suspending height decrease during the process, and it does not decrease with time any more when it is kept at the frequency of 20 Hz. Abruptly increased amplitudes for both cryostat and TMG observed with the increase of frequency are perhaps associated with their eigenfrequencies, respectively. Furthermore, we notice that the slight inclination phenomenon for cryostat can be observed with the decrease of side-suspending height, i.e., the top of the cryostat is slightly away from the TMG, and the bottom of it is close to the TMG to a
small extent. Thus we keep the laser displacement sensor 2 to aim at the middle of top of the cryostat to diminish the effect of it on the measurement.

a) The effect of vibration amplitude on the stability of the side-suspending maglev system.

The attenuation of the side-suspending height of the maglev vehicle with the vibration amplitude is shown in figure 5. The results in figure 5 indicate that the attenuation of side-suspension height increases with the augment of vibration amplitude. As we know that superconductor bulk captures some flux when it is field cooled to achieve superconducting state. The periodical vertical vibration for the side-suspending maglev system shown in figure 2 will cause the relative position between HTS bulks and the TMG to be changed periodically. According to the magnetic components of $B_x$ and $B_z$ at the height of 10 mm over TMG surface, as shown in figure 3, it will cause the bulks to experience an alternating magnetic field. Some earlier results state that the guidance force is elastic with the lateral displacement in a certain extent [13]. However, in this experiment, with the increase of amplitude, the attenuation of side-suspending height of the maglev system increases continuously. This indicates that the vibration process leads to the AC loss due to HTS bulks’ experiencing the alternating magnetic field. Earlier results noted that the alternating magnetic field leads to an irreversible attenuation of the guidance force [14]. Ogawa et al. claimed that alternating magnetic field can lead to the temperature of HTS bulk to increase, and thus reduce the $J_c$ and trapped magnetic flux [15-17]. Furthermore, the guidance force declines with the decrease of the captured magnetic flux [13]. Therefore, in our experiment, it is observed that, with the increase in amplitude, the AC loss increases and further causes the attenuation of side-suspending height to increase.

![Figure 5. The attenuation of side-suspending height with the vibration amplitude of 1, 2, 3 and 4 mm at the gap of 10 mm.](image)

b) The effect of different side-suspending gap on the stability of the side-suspending maglev system.

The experimental results are shown in figure 6. It is shown that the vibration will cause the attenuation of the side-suspending height to increase with the increase of the side-suspending gap. For the traditional maglev mode, as the guidance force increases with the increase of the captured flux [13], the stiffness of the guidance force increases with the decrease of the suspending gap.
Therefore, when the side-suspending gap is smaller, magnetic flux captured by bulks is larger and so does the side-suspending stiffness, the bulks only need to drop a short distance to make up for the attenuation of guidance force caused by AC loss. For larger side-suspending gap, the side-suspending stiffness is smaller, for the AC loss induced by vibration, a larger distance is required for the side-suspending maglev to drop to make up for its AC loss. Therefore, it can be seen that, with the increase of the side-suspending gap, the vibration will result in the increase of the attenuation of the side-suspending height.

\[18-20\].

\[ H_0 - H_V \] (mm)

**Figure 6.** The attenuation of side-suspension height with vibration amplitude of 3 mm at the gap of 5, 8, 10, 13 and 15 mm

\[ H_0 - H_V \] (mm)

**Figure 7.** The attenuation of side-suspension height with the load of 0, 125, 250, 350 and 500g at the vibration amplitude of 3 mm and the gap of 10 mm

**c)** The effect of the load carried by the maglev system on the stability of the side-suspending maglev system.

In addition, we also measured the effect of vertical vibration on the side-suspending height under different load. The results indicate that the attenuation of side-suspending height increases with the increase of load, as shown in figure 7. It perhaps means that larger load leads to larger AC loss of the bulks, and thus the larger attenuation of the side-suspending height. Moreover, under the same maglev stiffness, the maglev system with larger load needs to descend a larger distance to regain the side-suspending carrying capacity to balance its total weight. Therefore, we observe that under vibration, the attenuation of side-suspending height increases with the augment of load.
It is necessary to be remarked that under the vibration, the side-suspending system carrying capacity will not continue to decay obviously with the increase of vibration time, as shown in figure 4. Furthermore, decrease of side-suspending height seems mainly to occur when the vibrator start to work with the largest amplitude. Similar effect of AC magnetic field on levitation force was experimentally investigated by Smolyak et. al [21]. It is pointed out that at the beginning of the application of AC magnetic field, the levitation force attenuates rapidly, and then tends to a constant value gradually. In addition, we note that although the vibration leads the side-suspending height to decrease for the system, the overall decay of side-suspending height is not more than 1.5 mm. Thus slight decrease in side-suspending height will not result in a significant decrease in centripetal levitation force [8].

4. Summary
The vertical vibration will cause the HTS bulks to undergo alternating magnetic field and cause the attenuation of side-suspending height to increase due to the AC loss. Increasing the side-suspending gap, vibration amplitude and the load of the maglev system will further cause the attenuation of side-suspending height to increase, respectively. However, as the overall decrease of side-suspending height is smaller than 1.5 mm, this will not have a greater impact on the centripetal levitation force and the stability of the side-suspending maglev system. Moreover, as we know that decreasing the working temperature of HTS may increase its performance and diminish AC loss apparently, the HTS components should work at a temperature much lower than 77K for the future application of HTS maglev system.

Acknowledgments
In this paper, the authors wish to thank the fund for the project support, including the Program of International S&T Cooperation (Grant No. 2013DFA51050), the National Nature Science Foundation of China (grant No. 51271155,51377138), the Fundamental Research Funds for the Central Universities under No. 2682016ZDPY10, Foundation of Key Laboratory of Magnetic Suspension Technology and Maglev Vehicle, Ministry of Education.

References
[1] Hull J R 2000 *Supercond. Sci. Technol.* **13** R1-R15
[2] Werfel F N, Floegel-Delor U, Rothfeld R, Riedel T, Goebel B, Wippich D and Schirrmeister P 2012 *Supercond. Sci. Technol.* **25** 014007
[3] Mukoyama S, Nakao K, Sakamoto H, Matsuoka T, Nagashima K, Ogata M, Yamashita T, Miyazaki Y, Miyazaki K, Maeda T and Shimizu H 2017 *IEEE Trans. Appl. Supercond.* **27** 3600804
[4] Raghunathan R S, Kim H D and Setoguchi T 2002 *Progr. Aerosp. Sci.*, **38** 469
[5] Ma G T 2013 *IEEE Trans. Appl. Supercond.*, **23** 3024
[6] Tsuda M, Susa T, Ohyama T, Ishiyama A and Kohayashi S 2000 *IEEE Trans. Appl. Supercond.*, **10** 894
[7] Ohyama T, Shimizu H, Tsuda M and Ishiyama A 2001 *IEEE Trans. Appl.Supercond.*, **11** 1988
[8] Liang Gang, Zhao Lifeng, Yang Jinlei, Ma Jiaqing, Zhang Yong and Zhao Yong 2015 *IEEE Trans. Appl. Supercond.*, **25** 3601406
[9] Zhou Dajin, Cui Chenyu, Zhao Lifeng, Zhang Yong and Zhao Yong 2017 *Supercond. Sci. Technol.* **30** 25019
[10] Zhou Dajin, Cui Chenyu, Zhao Lifeng, Zhang Yong and Zhao Yong 2017 *IEEE Trans. Appl. Supercond.* **27** 3600107
[11] Zhao Lifeng, Du Yidong, Pan Xifeng, Jiang Jing, Zhang Yong and Zhao Yong. *Rare Metal Mat. Eng.* In press.
[12] Yoshida Y, Uesaka M, Miya K 1994 *IEEE Trans. Magnetics* **30** 3503
[13] Wang X R, Song H H, Ren Z Y, Zhu M, Wang J S, Wang S Y and Wang X Z 2003 *Physica C*, **386** 536
[14] Zhang L C, Wang J S, Wang S Y and He Q Y 2007 *Physica C* **459** 43-46
[15] Ogawa J, Iwamoto M, Tsukamoto O, Murakami M and Tomita M 2002 *Physica C* **372** 1754
[16] Ogawa J, Iwamoto M and Yamagishi K 2003 *Physica C* **386** 26
[17] Yamagishi K, Ogawa J, Tsukamoto O, Murakami M and Tomita M 2003 *Physics C* **392-396** 659
[18] Johansen T H, Mestl H, and Bratsberg H 1994 *J. Appl. Phys.* **75** 1667
[19] Johansen T H, Yang Z J, Bratsberg H, Helgesen G and Skjeltorp A T 1991 *Appl. Phys. Lett.*, **58** 179
[20] Johansen T H, Bratsberg H, Yang Z J, Guo S J and Loberg B 1991 *J. Appl. Phys.*, **70** 7496
[21] Smolyak B M, Ermakov G V and Chubraeva L I 2007 *Supercond. Sci. Technol.* **20** 406