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Dynamic response characteristics of the high-temperature superconducting maglev system under lateral eccentric distance

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ABSTRACT

Off-centre operation of high-temperature superconducting (HTS) maglev systems caused by inevitable conditions such as the misregistration of vehicle, crosswind and curve negotiation, may change the distribution of the trapped flux in the HTS bulks and the magnetic interaction between HTS bulks and the PMG. It impacts on the performance of HTS maglev, and more seriously makes the maglev vehicle overturned. Therefore, understanding the performance of the HTS maglev in off-center operation is very important. In this paper, the dynamic response characteristics of a cryostat with twenty-four onboard YBaCuO superconductor bulks were experimentally investigated at different eccentric distances under loads before the initial FC process. Parameters such as vibration accelerations, displacement, natural frequency and dynamic stiffness were acquired and analyzed via the B&K vibration analyzer and laser displacement sensors. Results suggest that the natural frequency and dynamic stiffness of the maglev vehicle would be obviously reduced with the eccentric distance, posing negative effects on the stability of HTS maglev.

1. Introduction

Since 1911 Onnes finding the superconductivity [1], the discovery of high-temperature superconducting (HTS) materials by Bednorz and Muller in 1986 is the most significant development of the application of superconducting which breaks through the limitation of low critical temperature of 30 K [2], noteworthy to mention that the critical temperature of YBaCuO has been increased to 90 K beyond the liquid nitrogen temperature of 77 K. And these discoveries contribute to various potentials for engineering applications such as the superconducting maglev, the flywheel energy storage system, superconducting bearings, liner motors and high power density generators [3–5]. In the field of transportation comparing with conventional wheel–rail vehicles, the HTS maglev with unique flux-pinning property can realize passive self-stable levitation without any necessary control, non-contact and low noise, meeting all demands of the 21st century's high-speed transportation in energy conservation and environmental protection with the development of the society. After the success of the first man-loading HTS Maglev test vehicle in China in 2000 [6], the HTS maglev system has drawn much attention from all over the world, the German concept prototype "SupraTrans I" was developed in IFW, Dresden in 2004 [7], then in 2014 a 200 m full-scale HTS Maglev vehicle operational line "MagLev-Cobra" was built by Federal University of Rio de Janeiro in Brazil [8].

As a novel transportation system, the study on the vehicle system dynamics of the HTS Maglev is just at the beginning and many problems remain to be researched and solved, of which the performance variation of the HTS Maglev system in eccentricity is an important one, which often happens in the practical operation and mainly results from two aspects: one is that the vehicle is not located above the center of the permanent magnet guideway (PMG) during the initial field cooling (FC) process; the other is that it will probably deviate from the PMG curve to some extent due to the centrifugal force at high speed. Previously a great quantity of work has been done, the electromagnetic forces (levitation force and guidance force) of a HTS bulk levitation unit were experimentally investigated by different eccentric distances (EDs, which is the horizontal distance between the geometric center of the superconductor bulk unit and the center-line of the PMG) based on the quasi-static study [9,10], and the influence of lateral displacement with translational symmetry on the levitation force was also theoretically analyzed in a magnetic-energy minimization procedure [11], and the dynamic response characteristics of the HTS Maglev system located above the center of the PMG at different field-

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Nomenclature

DS	dynamic stiffness
ED	eccentric distance
FC	field cooling
FCH	field-cooling height
HTS	high-temperature superconducting
NF	natural frequency
PMG	permanent magnet guideway
WH	working height

cooled positions also have been researched, including the tests of external excitation to the vehicle and free vibration in the maglev vehicle operation [12–14]. However, the dynamic response characteristics of the HTS Maglev system with different EDs that severely impact on the stability have not been studied extensively.

To further study the variation characteristics of the HTS maglev vehicle in eccentricity, this study comprehensively focuses on the dynamic response parameters of the HTS maglev system with different EDs, including the essential natural frequency (NF), dynamic stiffness (DS) and working height (WH) of a maglev cryostat under different field-cooling heights (FCHs) and levitation loads. The relationship between the changing parameters and the eccentricity was analyzed in this paper, and obtained results are helpful to improve the stability of the HTS maglev in practical running.

2. Experimental setup and procedure

As presented in Fig. 1, the simplified experimental setup is mainly composed of three parts: a cryostat, a PMG and an acquisition system. The cryostat is regarded as a maglev vehicle model, which contains 24 rectangular three-seeded melt-textured YBaCuO bulks with a dimension of $64 \times 32 \times 13$ mm^3 made by ATZ GmbH, Germany [15]. The values of the width and length of these two columns of HTS bulks in the cryostat are 128 mm and 384 mm, respectively. The total weight of the cryostat filled with liquid nitrogen is about 18 kg.

The PMG is made of Nd–Fe–B permanent magnets and arranged in Halbach type with a cross section of 120×25 mm^2. Fig. 2(a) shows the magnetic field environment around the applied Halbach-type PMG. And Fig. 2(b) gives the magnetic flux distribution along its transverse direction at a height of 15 mm. The origin point is at the left edge of the PMG in the horizontal plane. It can be found that the strongest magnetic field lies in the middle of the PMG.

Based on the method of pulse excitation, the acquisition system, consisting of a B&K vibration analyzer (3560C), two laser displacement sensors (LK-G80), two accelerometers (4507B-004) and a hammer (8206) were used to acquire and analyze the vibration acceleration and displacement signals shown in Fig. 1 and the specifications of them are listed in Table 1. The impulse force applied to excite the cryostat was produced by the special hammer with a piezoelectric force transducer mounted on its head. The hammer head is made of soft rubber to concentrate the energy at low frequencies. Two single axial type accelerometers marked *A* and *B* were fixed on the top of the cryostat to measure the vibration response signals from transverse direction and vertical direction respectively, when the hammer strikes vertically on the upper surface center or the side face center of the cryostat. Then the B&K vibration analyzer could obtain the amplitude-frequency response upon the Fourier analysis by the Pulse software. Meanwhile, the vertical displacement was measured in two points at the left and right edges of the cryostat though two Charge-coupled Device laser displacement sensors from LK-G Series of KEYENCE Company fixed on the blocks.

In the experiment, the cryostat was laterally moved to a predesigned position before the FC process to simulate a typical off-center operation, as described in Fig. 3(b). Then the cryostat with HTS bulks was cooled by liquid nitrogen for 60 min at a FCH. After the HTS bulks were cooled completely, the vehicle model was released and levitated freely above the PMG. Subsequently, an impulse force by the hammer was applied to the cryostat in the vertical/lateral direction. Meanwhile, the B&K vibration analyzer and laser displacement sensors recorded and analyzed the dynamic signals such as vibration acceleration, NF and WH. The procedure was continuously repeated through loading approximately 5 kg at a time until the total loading weight reached 20 kg, then unloading in the same way. In addition, EDs were set as 0 mm, 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, and 30 mm, and FCHs were chosen to be 15 mm, 25 mm, and 35 mm, respectively. Another thing should been noted is that the artificial error was inevitable in this experiment, such as the inaccuracy of the predesigned location of the cryostat above the PMG during the FC condition, the different strength and point of the excitation by the hammer at each time, and the measurement error of WH caused by the shaking cryostat. Therefore, we tried to avoid these mistakes in the operation and repeated the experiment many times to improve the accuracy.

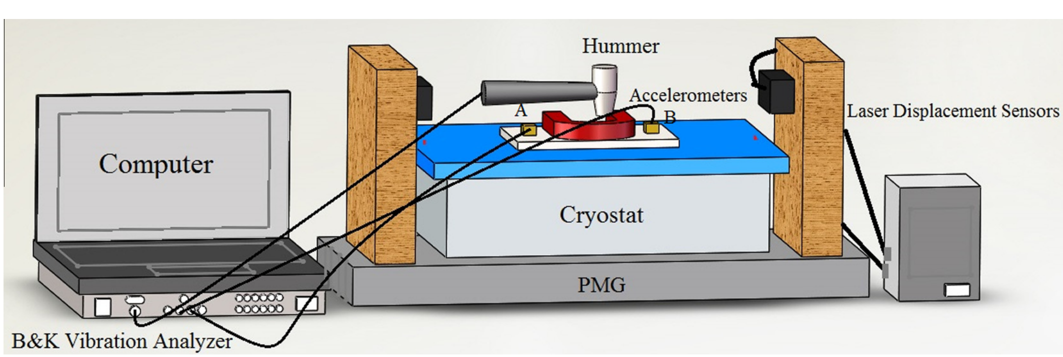

Fig. 1. View of the experimental setup including a cryostat, a PMG and an acquisition system. Two accelerometers, *A* and *B*, were fixed on the top of the cryostat, and the cryostat is levitating above a PMG.