Cryogenics 86 (2017) 1–6

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Research paper

A magnetic levitation rotating plate model based on high-T_c superconducting technology

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ARTICLE INFO

Article history:
Received 13 April 2017
Received in revised form 18 June 2017
Accepted 21 June 2017
Available online 22 June 2017

Keywords:
High temperature superconductor
Magnetic levitation
Display model
Rotatable plate
Permanent magnet array

ABSTRACT

With the wide requirements of the training aids and display models of science, technology and even industrial products for the public like schools, museums and pleasure grounds, a simple-structure and long-term stable-levitation technology is needed for these exhibitions. Opportunely, high temperature superconducting (HTS) technology using bulk superconductors indeed has prominent advantages on magnetic levitation and suspension for its self-stable characteristic in an applied magnetic field without any external power or control. This paper explores the feasibility of designing a rotatable magnetic levitation (maglev) plate model with HTS bulks placed beneath a permanent magnet (PM) plate. The model is featured with HTS bulks together with their essential cryogenic equipment above and PMs below, therefore it eliminates the unclear visual effects by spray due to the low temperature coolant such as liquid nitrogen (LN_2) and additional levitation weight of the cryogenic equipment. Besides that, a matched LN_2 automation filling system is adopted to help achieving a long-term working state of the rotatable maglev plate. The key low-temperature working condition for HTS bulks is maintained by repeatedly opening a solenoid valve and automatically filling LN_2 under the monitoring of a temperature sensor inside the cryostat. With the support of the cryogenic devices, the HTS maglev system can meet all requirements of the levitating display model for exhibitions, and may enlighten the research work on HTS maglev applications.

1. Introduction

For thousands of years, human beings dreamed of defying gravity. Some successful attempts appeared up until more recent times like balloons, planes, rockets and so on. Lately, there seems to be a resurgence of public interests in the concept of magnetic levitation (maglev). Schools, even in kindergartens and primary schools, desperately need training aids and models to display the amazing maglev phenomenon for the popularization of science to students. As well known, after decades of researches and developments, the existing and promising maglev technologies in industrial applications can mainly be divided into three types [1,2], which are electromagnetic levitation, electrodynamic levitation, and superconducting magnetic levitation, respectively. But, not all of them are suitable for exhibitions. Electrodynamic levitation has little potential in a size limited model fabrication, because it requires a relative running speed to maintain the levitation state, which needs extra driving power and may cause danger during displaying. According to Earnshaw's theorem [3], no rigid array of magnets or charges can create the three-dimensional potential well for stable levitation in free space. Therefore, electromagnetic levitation employing electromagnets must consider a highly-precise monitor and real-time controlling system [4,5]. The most important issue is that its controllable stable-levitation region is much confined as well as its anti-disturbance capability.

Maybe the magnetic levitation based on high temperature superconducting (HTS) technology is the best way to solve these issues above. For the unique flux pinning property [6–8], HTS bulk $YBa_2Cu_3O_{7-x}$ (YBaCuO) has become the target which researchers are chasing since its first discovery in 1987 [9]. It is able to stably levitate objects dozens of times its own weight in an applied magnetic field, which is free of external power supply and controlling system [10–12]. Attributed to these advantages, many training aids and models with HTS technology have been developed. In 2004, Stephan et al. developed a small scale maglev vehicle prototype [13]. Yang et al., designed a small maglev car model with YBaCuO bulks in 2006 and also a spacecraft model flying around a tellurion with the same material in 2010 [14,15]. Our group developed a hybrid HTS maglev sculpture model with a double-layer axial levitation structure in 2013 [16]. These models share a same characteristic in common that the small maglev models run along the

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http://dx.doi.org/10.1016/j.cryogenics.2017.06.002
0011-2275/

direction of permanent magnets (PM) paved on the foundation. Different from the general designs, in this paper, we came up with an axisymmetric system to levitate a circular PM plate rotating above the superconductors in order to achieve a fantastic visual effect for display in public.

2. Design concept

For lifting a display platform model by a PM rotating plate, audiences' feelings should be the most significant aspect as a designing target taken into account. And it is mostly reflected in the following aspects including free levitation, visible levitation height and related equilibrium range, levitation weight, and rational dimensions. There is no doubt that a comparatively high levitation height, heavy levitation weight, and large model dimensions are likely to draw in crowds. Based on these, basic requirements from the point view of audiences' feeling are considered and some main design parameters are listed in Table 1.

The present common HTS maglev models are usually made with PMs below as the base and HTS bulks above as the levitator. Such a structure and the function definition are not competent to realize a long-term and free levitation. On the one hand, as the levitator, more unnecessary weight from liquid nitrogen (LN_2) and a thermally insulated cryostat reduces the allowable load weight for the display platform model and the display object. Closing to LN_2 may also do harm to the materials of display model itself. On the other hand, the spray caused by low temperature of LN_2 will bring unclear visual effects for audiences. People can hardly catch sight of the levitation phenomenon by looking through the air gap full of spray. Therefore, this paper comes up with an idea of exchanging the positions and functions of HTS bulks and PMs. In our design, the HTS bulks as the base was fixed in the upper end of a LN_2 cryostat while the PM array works as the rotational levitator.

Fig. 1(a) gives the internal mechanical drawing of the cryostat of this HTS maglev rotating plate display model. This cryostat mainly consists of three parts, which are the inlet of LN_2, the outlet of gaseous N_2, and the LN_2 container. The HTS bulks are inside the inner upper end of the cryostat and they are only 4.5 mm away from the outside surface of the cryostat. A thin top wall can assure enough net levitation height for excellent visual effects. Each HTS bulk is of 30 mm in diameter and 18 mm in thickness, and the arrangement of HTS bulks is schematically shown in Fig. 1(b) to help the function of rotation of the levitated plate and the lifting object [17]. The cylindrical bulks made of YBaCuO superconductor materials are arranged into three circles. The first circle contains only one bulk, the second six, and the third twelve. The whole arrangement presents a beautiful hexagon shape, and 19 bulks in total can provide a considerable levitation force.

The cryostat design inherits the conventional characteristic of the double layers, but it does have its own traits. It is worth mentioning that the inlet of LN_2 is set at the bottom of the cryostat. LN_2 is transported into the cryostat from a self-pressurized LN_2 container. With the inner liquid level increasing, LN_2 begin to touch HTS bulks, and after a quarter the HTS bulks will convert into superconducting state. The gaseous N_2 can flow out from the curved pipe which is set behind the cryostat during the gasification process of the inner LN_2. This structure avoids filling the air gap with lots of hazy spray, and the visual effects get greatly improved consequently. Moreover, a scale ruler is stuck to measure and show an intuitionistic understanding of the levitation height as shown in Fig. 1(c).

Table 1
Design parameters of the HTS magnetic levitation rotating plate model.

Parameter	Value
Net levitation height	>15 mm
Net levitation load	5 kg
Levitated plate	200 mm in diameter, and 20 mm in thickness
Observation height	1200–1300 mm

Considering the requirement of high coercive force, high remanent magnetic induction and high magnetic energy product, NdFeB should be the most suitable choice for the fabrication of levitated PM plate. But in fact, a single PM can hardly provide enough strong magnetic fields. Therefore, a new kind of PM plate assembled in Halbach array shown in Fig. 2 was adopted in our system. The Halbach array has wide applications in electrical machines, flywheel systems, and maglev transportation, because it can gather most of the magnetic field energy to its working surface. Fig. 2(b) depicts the magnetic field concentration characteristics at the bottom surface of the designed Halbach-type disk. The arrangement has 4 PM array circles, among which the second circle has 9 PM pieces, and the fourth circle has 18 PM pieces. Both the first and third circles are made of a full ring PM. The whole plate is of 200 mm in diameter and 20 mm in thickness, and its weight is 4.27 kg.

At the early stage, the LN_2 filling process was finished manually, and it was with at most six cryostats that the operation efficiency can be at a favorable level [18]. Recently there is a general trend of replacing manual labor by LN_2 filling automation devices. Automatic operation cuts risk of potential danger to workers and greatly improves the working efficiency, which is a better choice for the LN_2 filling process. We put up with an appropriate solution by using a self-pressurized LN_2 container to pressure LN_2 into the cryostat, and set a temperature sensor inside the cryostat and a solenoid valve in the LN_2 input pipe. In our system, the continued refilling LN_2 is controlled by the on-off state of the solenoid valve which is determined by the monitored temperature of the temperature sensor attached on the upper inner-surface of the cryostat (see Fig. 3b). When the temperature inside the cryostat is above 103 K, the solenoid valve opens and lets LN_2 flow in, always maintaining a required low-temperature environment for YBaCuO bulks. Until the temperature is refreshed below 95 K, the valve starts the off state. The threshold temperature setting of solenoid is referenced from experience. The temperature sensor was placed above LN_2 level, so the threshold temperature values we chose are higher than both 77 K (the temperature of LN_2) and 93 K (T_c, the critical temperature of YBaCuO) [9]. By adjusting the pressure valve, LN_2 can flow out of the container through the solenoid valve into the cryostat by giant pressure. Coupled with the control system, the self-pressurized system simplifies LN_2 filling operation and keeps the working low temperature more precisely and quickly. Pictures of the whole system in 3D model are shown in Fig. 3.

With the innovative designs mentioned above, the maglev rotating plate model can achieve excellent visual effect. The PM plate is able to be levitated about 20 mm approximately above the cryostat. In the horizontal plane, the maglev plate can rotate freely around its axis of symmetry with a comparatively high speed. Fig. 4 gives the levitating visual effect by photographs.

3. Experiments and simulations

One of the prominent advantages of HTS maglev is its large tare-load ratio. Although each HTS bulk is only a few