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High-efficiency and low-cost permanent magnet guideway consideration for high-T_c superconducting Maglev vehicle practical application

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Abstract
In order to improve the cost performance of the present high-T_c superconducting (HTS) Maglev vehicle system for practical application, the multi-pole permanent magnet guideway (PMG) concept was introduced. A well-known double-pole Halbach PMG was chosen as a representative of multi-pole PMGs to compare with traditional monopole PMGs from the point of view of levitation efficiency and cost. Experimental results show that YBCO bulks above the double-pole Halbach PMG can exhibit better load capability and guidance performance as well as dynamics stability at the applied working height between the bulk HTSC and the PMG due to a more reasonable magnetic field distribution at the working range of bulk HTSC. Furthermore, the double-pole PMG configuration can play a more important role in improving guidance performance due to the potential-well field configuration. By comparing with former 'century' PMGs, the double-pole Halbach PMG shows another remarkable advantage in reducing the cost of levitation. As another necessary issue, magnetic field homogeneity and the corresponding magnetic drag force of a double-pole Halbach PMG has been considered by experiment in spite of the above highlights. Synthetically, the multi-pole Halbach PMG design is concluded to be one important choice for future HTS Maglev vehicle applications because of its high efficiency and low cost.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Since the discovery of high temperature superconductors (HTSC) in 1986 [1], significant improvements in bulk HTSC material have been achieved during the past 20 years [2] which make for its potential for various engineering applications. A most popular application of bulk HTSC is magnetic levitation (Maglev). Unlike other Maglev concepts, bulk HTSC with unique flux-pinning properties can realize self-stable levitation without any active control [3]. Utilizing the advances in the passive self-stable characteristic, magnetic levitation with bulk HTSC has been widely used in the fields of non-contact bearings [4–6], flywheel energy storage systems [7–9], levitated linear transportation systems [10–13], motors/generators [14, 15], etc [2].

A high temperature superconducting (HTS) Maglev vehicle, characterized by high speed, environment friendly, low maintenance and low energy consumption, is proposed as one of the most promising future transportation tools [16]. The feasibility of the man-loading HTS Maglev vehicle was first verified in China at the end of the last century [10].

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So far, over 40 000 passengers have used the vehicle, and it has traveled back and forth for about 500 km. After 7 years' running history, the levitation performance of the vehicle is almost the same as in the beginning and its long-term stability has been proved [17]. During these seven years, the practicality of the HTS Maglev vehicle has been much promoted in people's life, such as research on permanent magnet guideway (PMG) optimization [18–21], electromagnetic turnout switch [22], propulsion method [23], gradeability [24], vibration characteristics [25–27], low speed running stability [28, 29], AC magnetic field influences [30], test line consideration [31], etc [32].

In engineering, cost is always an important issue to be considered in all practical superconducting applications. The Brazil group [31] has analyzed and compared the construction costs of a 1 km HTS Maglev line with the same costs for a light rail vehicle (LRV). It is concluded that the HTS Maglev line will be cheaper than the LRV one, mainly because of the low infrastructure costs. As to the total cost of the HTS Maglev vehicle system, the cost for permanent magnets (PMs) paved along the train line is largest. In order to reduce this cost, how to use iron as the rail to replace the PMG has been studied but needs more work due to the limited stable levitation range [33, 34]. Despite about 5000 N m^{-1} levitation capability at a levitation height of 15 mm, responding to 2–4 N cm^{-2} levitation density and YBCO bulk weight to levitation load ratio of 20–30 for three present man-loading HTS Maglev test vehicles [10–12], there is still a large area in which to improve the cost performance. From this viewpoint, a multi-pole PMG concept is introduced into the HTS Maglev vehicle system and further compared with the traditional monopole PMG by evaluating load capability, guidance performance, dynamics stability, magnetic field homogeneity and cost.

2. Experiments

2.1. Monopole and multi-pole PMG descriptions

At present, a monopole PMG is the most popular style of HTS Maglev vehicle system [10–12, 18]. The most popular structure is that two PMs with opposite horizontal magnetization directions are connected by flux-concentration iron with a single peak in the vertical component of the magnetic field, as shown in figure 1. The structure is simple, and this monopole PMG is easy to install. With the iron elements between the PMs, a stronger gradient of the magnetic field is achieved for higher levitation stiffness, which results in about 1 ton load [10] for the present HTS Maglev test vehicle.

However, an axially symmetric HTS magnetic bearing with only 200 mm diameter also realizes about a 1 ton load in two representative applications [5, 6]. It is reasonable to believe that the high load capability of the axially symmetric superconducting magnetic bearings (SMBs) is mainly attributed to the PM rotor structure. In the general SMB design, the PM rotor is composed of multi-pole PMs [4–6] for larger force stiffness because one pole can form a higher magnetic field region. More numbers of poles is effective in enhancing the stability [35]. Applying the multi-pole magnetic

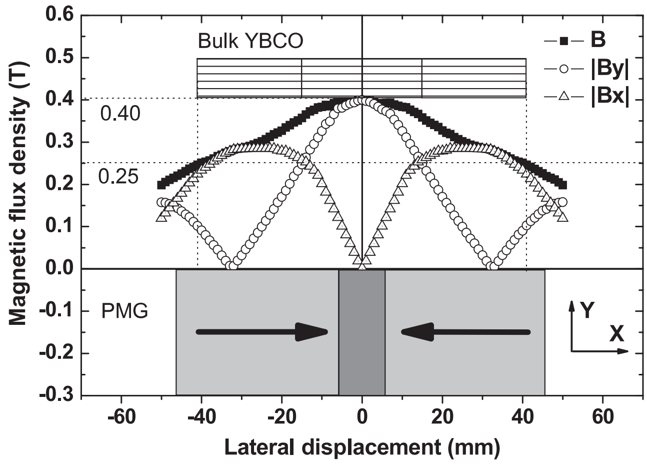

Figure 1. Configuration and magnetic field distribution at 15 mm gap of the traditional monopole PMG.

field merit to the HTS Maglev PMG design, the efficiency is expected to be improved by the same PM material cost by the reasonable design and arrangement of bulk HTSC. In this paper, a double-pole PMG is chosen first as a representative of the multi-pole PMG.

PM design with a Halbach array [36] is characterized by using a PM as the magnetic flux-collector, not iron, for a higher magnetic field, which has one particular benefit of concentrating the magnetic field in the applied region. Up to now, this has got more attention in various applications of particle accelerators, magnet bearings [37], electrical machines and Maglev designs [38–40]. So a double-pole PMG with Halbach array is designed and fabricated to verify its feasibility in an HTS Maglev vehicle system [21] as shown in figure 2. Two vertical magnetic field peaks appear obviously at the two poles. In order to compare them, the double-pole Halbach PMG has nearly the same PM cross-sectional area as a traditional monopole PMG, 3900 and 4000 mm^2, respectively. More details about the two PMGs can be found in [21]. In the following sections, the two PMGs will be carefully compared from several viewpoints which must be considered in practical applications.

2.2. Static force and stiffness experiments

In the HTS Maglev vehicle system, the onboard levitator is composed of many small YBCO bulk elements [10]. A levitation unit composed of seven cylindrical single-domain melt-textured YBCO bulks with diameter of 30 mm and height of 18 mm was extracted to investigate the interactions with the two equivalent PMGs. The bulks were arranged compactly into three columns along the PMG, as shown in the inset in figures 3, 4, 6, 8 and 11. Static force and stiffness are two important parameters in evaluating load capability and static stability of a levitation system. In this paper, static levitation force, guidance force and the respective stiffnesses were obtained by a self-developed HTS Maglev measurement system [41]. As a representative superconducting Maglev experimental condition, a field-cooling height (FCH) of 30 mm

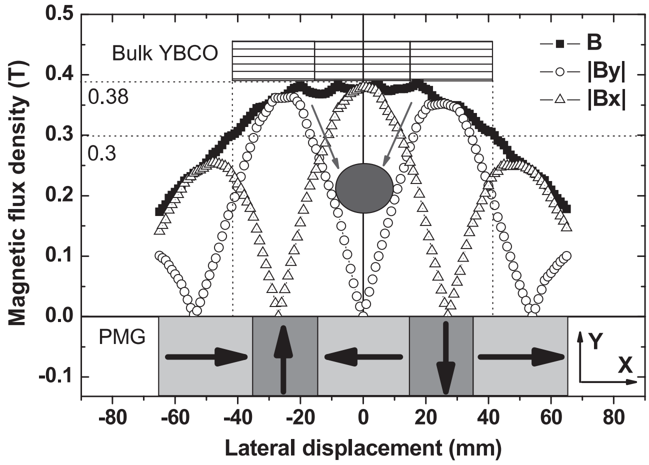

Figure 2. Configuration and magnetic field distribution at 15 mm gap of the double-pole Halbach PMG.

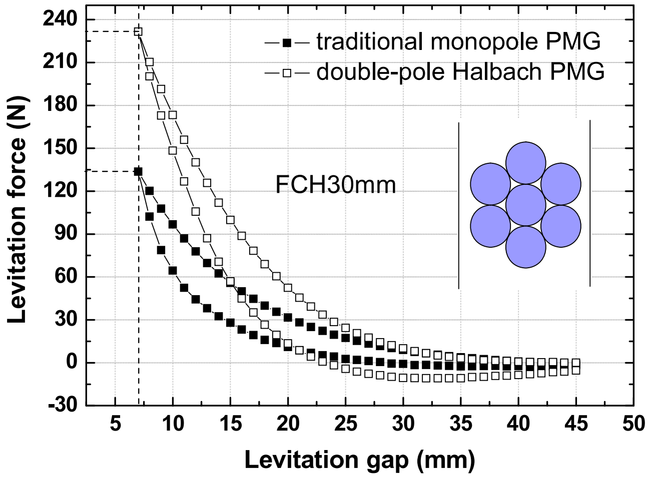

Figure 4. Levitation force comparison of a levitation unit above two PMGs at a field-cooling height of 30 mm.

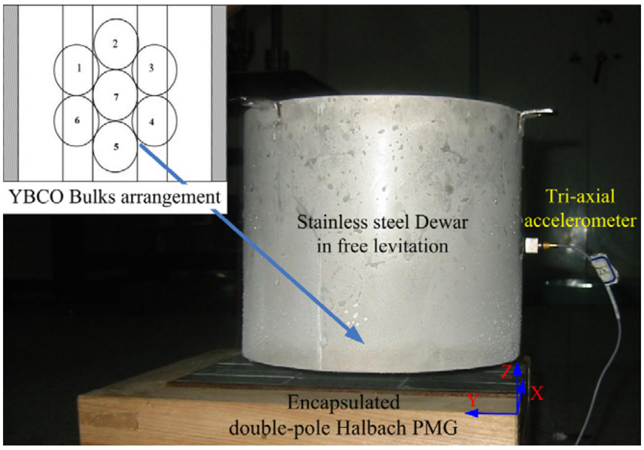

Figure 3. Experimental picture of dynamic impulse response experiments.

and measuring height (MH) of 15 mm are chosen because they lead to the optimum working method for the present HTSC–PMG system [26, 42].

2.3. Dynamic impulse response experiments

Besides static performance, dynamic vibration characteristics and stability are also very important for the running of an HTS Maglev vehicle system. In order to get dynamic parameters like dynamic stiffness and damping coefficient, impulse response experiments were applied to a simplified HTSC–PMG levitation system. The levitation unit, composed by seven bulks, was rigidly fixed to the bottom of a cylindrical stainless steel Dewar. The bulk unit was field-cooled at a certain FCH at the center of the PMG. After about 15 min cooling time, the Dewar was released and then levitated at an equilibrium position against its weight of 3.45 kg, as shown in figure 3. Then, an impulse force was applied to excite the vibration mode of the levitated Dewar by using a hammer. The responding vibration signals were collected and analyzed by a pulse analyzer from B&K Company using a tri-axial accelerometer attached to the surface of the Dewar. From vibration curves in the time domain and frequency domain, the resonance frequency and damping ratio of the HTS Maglev system could be obtained.

As the HTSC levitation system can be analogous to a quasi-spring system [43], the two-dimensional dynamic equation of the levitated unit over the PMG in the vertical direction can be simplified as

$$m\ddot{z} + c\dot{z} + kz = f, \tag{1}$$

where z is the vertical displacement of the levitation Dewar, m is its mass, k is the stiffness, c is the damping coefficient and f is the impulse force on the Dewar.

In frequency domain, equation (1) is transformed into

$$\ddot{z} + 2\gamma\omega_n\dot{z} + \omega_n^2 z = \frac{f}{m}, \tag{2}$$

where $\gamma = c/(2\sqrt{km})$, $\omega_n = \sqrt{k/m}$, γ is the damping ratio and ω_n is the resonant angle frequency.

Similarly, if the vertical displacement z is replaced by a lateral displacement x, we can obtain the lateral dynamic parameters. In the impulse response experiments, both the vertical and lateral vibration characteristics of the levitated unit above two PMGs were investigated at FCHs of 40, 30 and 20 mm.

3. Results and discussion

3.1. Static force and stiffness characteristics

Figure 4 shows the levitation force comparison of the levitation unit above two PMGs at an FCH of 30 mm. The levitation force curves show an approximate exponential increase with a decrease in the measurement gap from 45 to 7 mm. When the bulks returned to their origin, an obvious hysteresis phenomenon appeared in the levitation force curves, which is one of the essential properties of HTSCs caused by the magnetic flux moving into or out of the bulks. However,

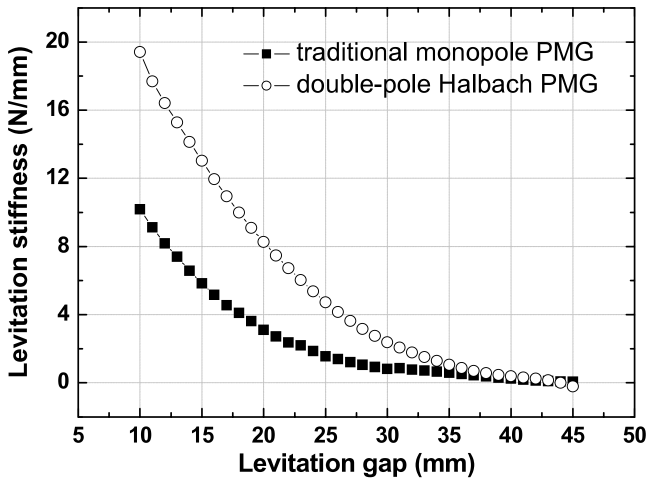

Figure 5. Levitation stiffness comparison of a levitation unit above two PMGs at a field-cooling height of 30 mm.

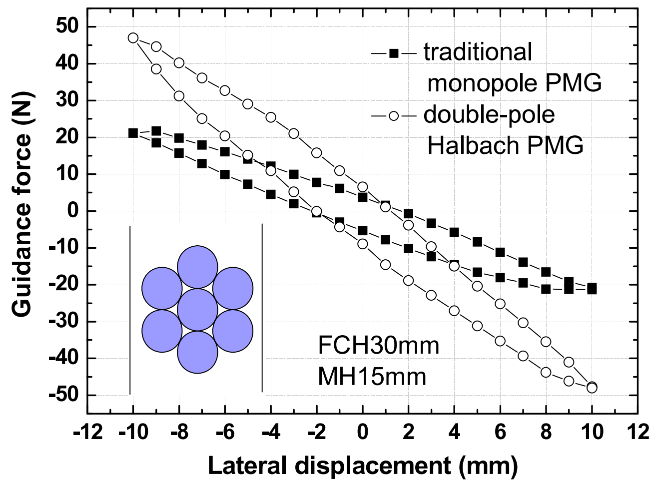

Figure 6. Guidance force comparison of a levitation unit above two PMGs at a field-cooling height of 30 mm and measurement height of 15 mm.

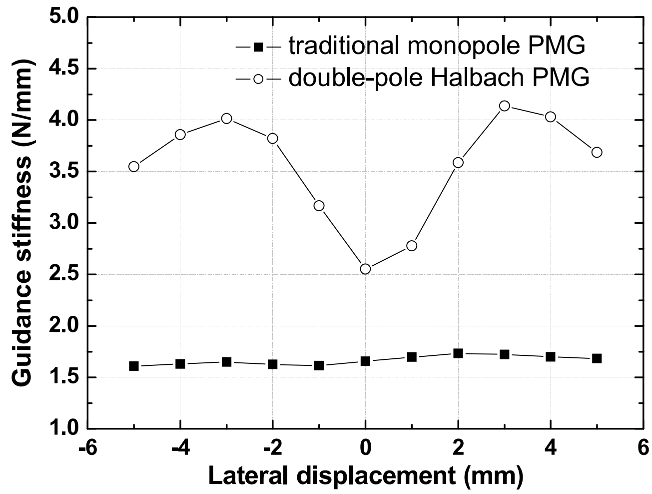

Figure 7. Guidance stiffness comparison of a levitation unit above two PMGs at a field-cooling height of 30 mm and measurement height of 15 mm.

different external PMG fields lead to different flux penetration and their motion in the bulk HTSC. In figure 4, the same bulk unit with the double-pole Halbach PMG gets a bigger levitation force and hysteresis loop than the traditional monopole PMG. At the smallest gap of 7 mm, the maximum levitation force is 231.5 N for the former, which is 1.73 times larger than the latter of 133.7 N. The bigger force and hysteresis indicate that the double-pole Halbach PMG produces a better magnetic field distribution at the interacting range with the bulk unit. Looking at figures 1 and 2, it is found that the average magnetic flux density at a gap of 15 mm is 0.328 T above the traditional monopole PMG, while it is 0.36 T for the double-pole Halbach PMG at the 82 mm width area of the levitation unit. The average field, not the peak magnetic field factor, is the main factor in levitation force and hysteresis. The average magnetic field embodies most of the flux motion tendency in HTSC. The double-pole Halbach PMG has the greater possibility of increasing its average magnetic field by broadening the strong magnetic region with two vertical magnetic field peaks (figure 2).

The corresponding levitation stiffnesses are shown in figure 5. Similar to the levitation force curve, the levitation stiffness curve shows an approximate exponential increase with the decrease of the levitation gap. The levitation stiffness of the bulk unit above the double-pole Halbach PMG is bigger than that of the monopole PMG from a gap of 40 to 7 mm. At the smallest gap of 7 mm, the levitation stiffnesses are 10.2 and 19.4 N mm^{-1}, respectively, while, for a larger gap over 40 mm, the two curves are close to each other, and even cross. That is, the double-pole Halbach PMG does not have an advantage over the monopole PMG at large levitation gap.

For an HTS levitation system, guidance force is used to evaluate whether the system is stable in the lateral direction and its restoring capability. Figure 6 shows the guidance force comparison of the seven-bulk levitation unit above two PMGs at an FCH of 30 mm and MH of 15 mm. Due to the field-cooling condition, the two guidance force curves both imply a stable Maglev system where a restoring force is generated against the lateral displacement. The bulk unit above the double-pole Halbach PMG can have a better guidance performance and bigger hysteresis loop than that above the monopole PMG. At the maximum lateral displacement of -10 mm, the maximum guidance force is 47.0 and 21.1 N, respectively, for the two PMGs. The guidance force ratio is 2.2, which is larger than the levitation force ratio. Figure 7 shows the guidance stiffness comparison of the bulk unit above two PMGs at the same measurement condition. The two guidance stiffness curves look symmetrical about their origin at the lateral displacement range of -5 to 5 mm. It is clear that the guidance stiffness of the double-pole Halbach PMG is about 2–3 times larger than that of the traditional monopole PMG even when the guidance stiffness is at its smallest value. It is well known that guidance force performance depends on the quantity of trapped flux in bulks. On the one hand, the saturation trapped field of the experimental bulk is a little low and only about 0.26 T [43] at liquid nitrogen temperature, so a much smaller or larger applied magnetic field is not very

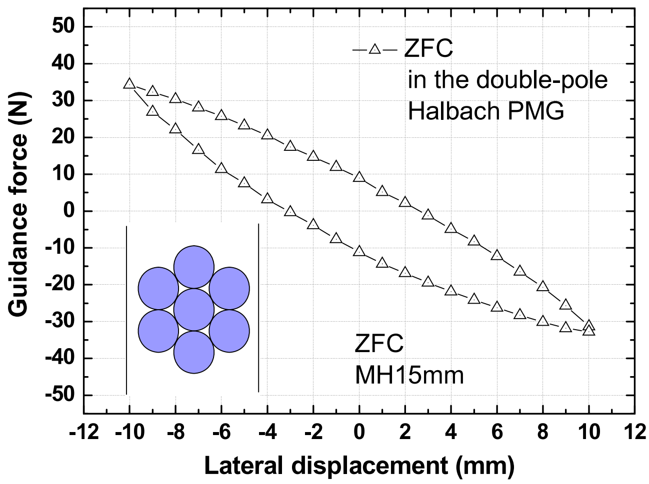

Figure 8. Guidance force of the seven-bulk levitation unit above the double-pole Halbach PMG in zero-field-cooling case and measurement height of 15 mm.

effective in enhancing its levitation and guidance capability. Moreover, the magnetic field distribution from 0.3 to 0.38 T by the double-pole Halbach PMG was thought to be more reasonable than that of the traditional monopole PMG from 0.25 to 0.4 T at the measuring position. So it is important to note that the PMG configuration should be optimized according to the performance of the bulk HTSC.

On the other hand, it is interesting to find that the double-pole Halbach PMG has an additional effect on the guidance performance of levitation bulks. Even at the zero-field cooling (ZFC), the seven-bulk unit can be able to realize stable levitation above the double-pole Halbach PMG, which is contrary to the case above the monopole PMG. The stable guidance force curves at ZFC with a double-pole Halbach PMG are shown in figure 8. It implies obviously that the stability is strong. At the maximum lateral displacement of -10 mm, the maximum guidance force of 34.26 N is obtained, which is 1.62 times larger than for the bulk unit at a FCH of 30 mm and WH of 15 mm above the monopole PMG. Moreover the value is 72.9% of the maximum guidance force (47.0 N) for an FCH of 30 mm and a WH of 15 mm above the same double-pole PMG. Different from the stable levitation in FC by flux-pinning of bulk HTSC, the stable levitation in ZFC results from the electromagnetic interaction between the bulk HTSC and the double-pole magnetic field. At the center of the double-pole Halbach PMG, an obvious magnetic potential well [44], marked by a dark circle in figure 2, is formed between the two peaks of the vertical magnetic field component. At the same time, three middle bulks just fall into the potential-well area. When a lateral displacement to any side happens to the bulks in the potential well, the vertical magnetic field at the bulk position will be changed to be stronger. According to Faraday's law of electromagnetic induction, a shielding current will be induced in the bulk material, and a corresponding repulsion Lorentz force resulting from the interaction of the induced current and the applied PMG field will be generated to resist the lateral displacement: thus the levitation is stable. This is also the reason why more pole numbers is effective in enhancing the levitation stability [35]. The above experiment indicates another way to realize stable superconducting levitation besides the FC condition in the PMG design. It is very attractive to use a potential-well field configuration to enhance the guidance performance in the multi-pole PMG design.

3.2. Dynamics stiffness and damping characteristics

Dynamics stability is very important for the running status of the HTS Maglev system. According to the former described experimental processes in section 2.3, dynamics parameters of a seven-bulk levitation unit, i.e. stiffness and damping coefficients, are evaluated from the impulse response experiments. The typical impulse response curves in the vertical direction are shown in figure 9, respectively for the time domain and frequency domain. The curve in the time domain is a typical damped free vibration curve and a peak which is regarded as the resonance frequency appears in the curve of the frequency domain.

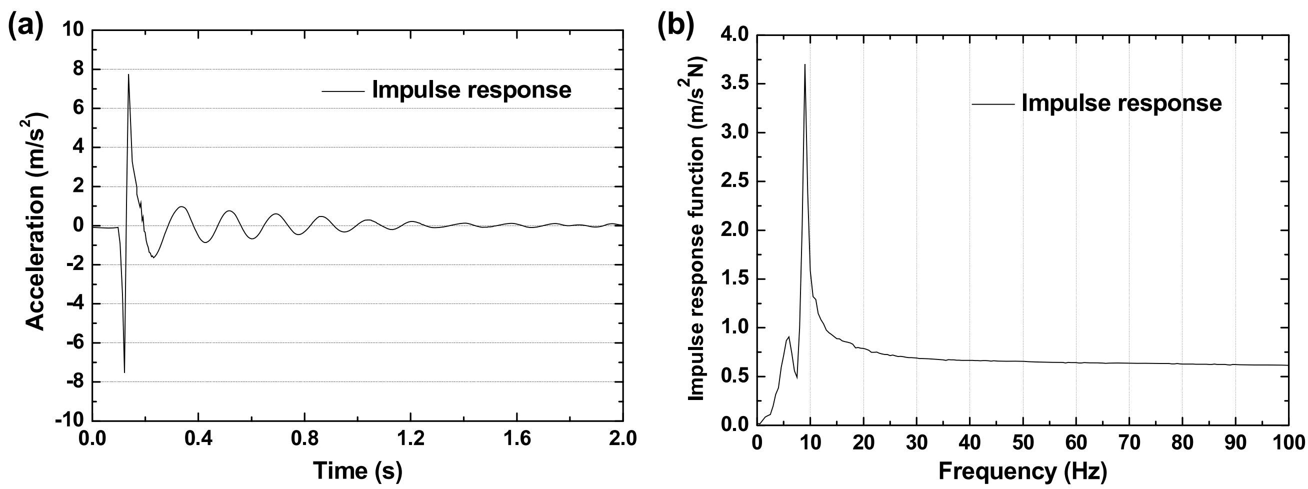

Figure 9. Impulse response curves of the seven-bulk levitation unit in time domain (a) and frequency domain (b).

Table 1. The vertical and lateral dynamic stiffness comparisons above two PMGs at different FCHs.

	Dynamic stiffness in vertical k_z (N mm^{-1})		Dynamic stiffness in lateral k_x (N mm^{-1})	
FCH (mm)	Monopole PMG	Double-pole PMG	Monopole PMG	Double-pole PMG
40	5.54	7.44	3.96	7.44
30	6.42	11.03	6.42	13.62
20	10.62	20.97	13.11	32.25

Table 2. The vertical and lateral damping coefficient comparisons above two PMGs at different FCHs.

	Damping coefficient in vertical c_z (N s m^{-1})		Damping coefficient in lateral c_x (N s m^{-1})	
FCH (mm)	Monopole PMG	Double-pole PMG	Monopole PMG	Double-pole PMG
40	11.63	8.84	13.96	15.47
30	16.58	12.09	9.37	14.96
20	15.36	17.62	15.27	23.05

The resonant frequency of the seven-bulk unit levitation system is around 10 Hz and increases with the decrease of FCH, which embodies the same trend for dynamic stiffness with FCH, as shown in table 1. In spite of PMG configuration and measurement direction, the dynamic stiffness was found to always be larger than the static stiffness (figures 5 and 7). This conclusion is consistent with early research results [4]. The dynamic stiffness of the bulk unit was thought to correlate with the quantity of trapped flux inside it. At lower FCH, higher trapped flux can bring about a larger dynamic stiffness, which is of benefit to the HTS Maglev system. At the same FCH, the dynamic stiffness of the bulk unit above the double-pole PMG is always larger than that of the monopole PMG, which implies that better dynamic stability can be achieved by the double-pole Halbach PMG.

Unlike the dynamic stiffness, another dynamic parameter of the damping coefficient does not show a monotonic relationship with FCH or trapped flux, as shown in table 2, which implies that some other factors, like vibration amplitude, can affect the damping coefficient. By almost the same magnitude of pulse force excitation, the trapped flux is still considered as the main factor for rough analysis of the HTS Maglev dynamic system because, for a well-known low damping HTS Maglev system, the main energy loss described by damping is the hysteresis loss of the bulk, which is related to its trapped flux. More trapped flux can cause more hysteresis losses so as to exhibit a bigger damping coefficient. Generally, the damping coefficient in table 2 still tends to increase with the decrease of FCH due to the greater trapped flux. At lower FCH such as 20 mm, the vertical damping coefficient with a double-pole Halbach PMG is larger than that of a monopole PMG. But the double-pole PMG does not retain the advantage at higher FCH. This is because the main magnetic field is concentrated at the low height of the double-pole Halbach PMG and is larger than that of the monopole PMG. As to the lateral damping coefficient, the same magnetic comparison situation happens so the double-pole PMG is always larger than the monopole PMG. As a larger damping coefficient implies a better anti-vibration ability, the bulk unit with the double-pole Halbach PMG has a better dynamic stability.

3.3. Another key issue

In the practical application, careful attention should be paid to the homogeneity of the infinite PMG. As is known, the homogeneous magnetic field distribution along the PMG's extended direction is the fundamental guarantee for the no-friction running of an HTS Maglev vehicle. Otherwise, there will be some magnetic drag forces produced in the running. This phenomenon is not expected and violates the advantage of the Maglev vehicle. Hence, before using any PMGs, their homogeneity should be checked carefully.

For the traditional monopole PMG using iron flux-collectors, the middle irons play a double role. On the one hand, they concentrate the magnetic flux into the center of the PMG with a strong field and gradient region. On the other hand, they can play a part in homogenizing the magnetic field by attracting the leakage flux. Such a structure using iron flux-collectors also brings some advantages like low eddy current losses and hysteresis losses in the HTSC. Even at very small applied distances, especially in SMB, it is still beneficial to realize a very homogeneous field. The effects of such a PMG structure using iron flux-collectors have been widely verified by successful HTS Maglev test vehicles [10–13] and SMB prototypes [4–6].

However, for the double-pole Halbach PMG without iron flux-collectors, its homogeneity is only guaranteed by the homogeneity of each piece of PM and the assembling precision. Due to the inevitable errors from magnetization and installation technology, it is believed to be difficult to install a perfect Halbach PMG. So, as a first step, the magnetic field fluctuations along the Halbach PMG direction are measured as shown in figure 10. As the PMG is assembled using many small PMs, air gaps may exist between every two PMs along the PMG, which is the main reason for the inhomogeneity of the PMG. The assembling error affects the inhomogeneity of the PMG much more at lower gaps, like 5 mm. The effect decreases with the increase in the gap. At a gap of 15 mm, the maximum magnetic field fluctuation is smaller than 3%. The corresponding magnetic drag force must be generated above such a magnetic field in the running case. In this step, we measured the magnetic drag force of the seven-bulk levitation

Table 3. Cost performance comparisons of three HTS Maglev designs with different PMGs.

	Former 'century' PMG	Monopole PMG	Double-pole PMG
PM cross-sectional area of single PMG (mm^2)	$152 \times 76 = 11552$	$80 \times 50 = 4000$	$130 \times 30 = 3900$
Number of onboard YBCO bulks (/m)[a]	200	200	200
Load capability ($N\ m^{-1}$)[b]	6081	~2700	~5850
Guidance force ($N\ m^{-1}$)[c]	750	~360	~760
Levitation density ($N\ cm^{-2}$)[d]	4.3	1.9	4.1
Load to bulk weight ratio	40.5	18	39
Levitation efficiency ($N\ cm^{-3}$)[e]	0.526	0.675	1.5
PMG cost[f] ($/km)	5400 000	1875 000	1825 000

[a] The size of applied bulks is 30 mm in diameter and 15 mm in height.
[b] At a gap of 15 mm in the case of ZFC.
[c] In the case of FCH 30 mm, MH 15 mm and at a lateral displacement of 5 mm.
[d] Levitation density is defined as the ratio of load capability to bulk HTSC area.
[e] Levitation efficiency is defined as the ratio of load capability to PM cross-sectional area.
[f] The cost is very dependent on the fluctuating price of PM materials.

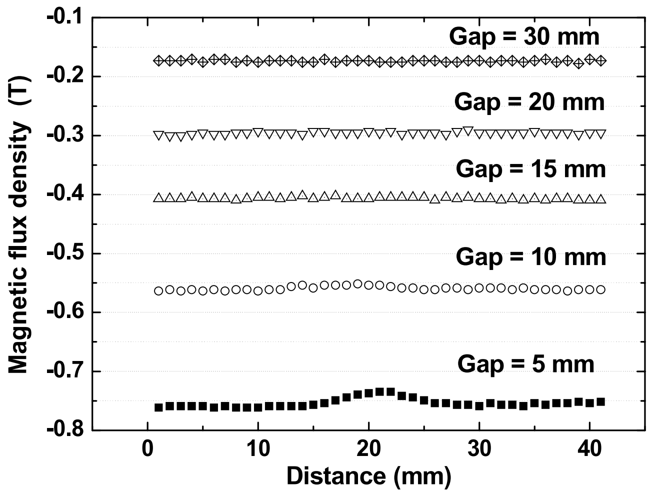

Figure 10. Magnetic field fluctuation along the double-pole Halbach PMG direction at different gaps. The air gap between the two PMs is at a value of 20 mm.

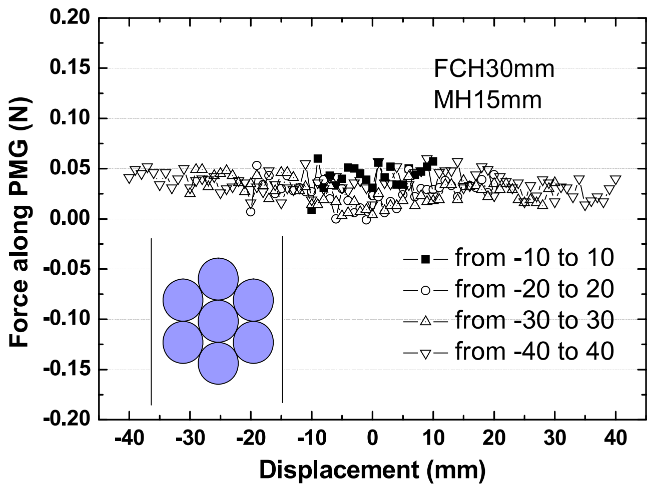

Figure 11. Drag force of the seven-bulk unit moving along the double-pole Halbach PMG direction for the case of an FCH of 30 mm and an MH of 15 mm. The air gap between the two PMs is at the origin.

unit moving along the double-pole Halbach PMG direction for the case of an FCH of 30 mm and an MH of 15 mm. The results are shown in figure 11.

It shows that the drag force is very small and only 0.08 N at maximum for the 3% inhomogeneity. Compared to the precision of 0.03 N of the measurement system [41], the drag force seems to be negligible at low measurement speed. So the HTS Maglev vehicle with the double-pole Halbach PMG is thought to be possible to realize low-friction running at a large gap (over 15 mm). If the HTS Maglev vehicle is chosen to run at a larger gap, this result is thought to be accepted at a low to middle running speed.

4. Economic aspects

Like most superconducting devices, initial construction costs are still the main obstacle for the HTS Maglev vehicle's practical application. Although the HTS Maglev vehicle system has an advantage of low infrastructure costs [31], the cost of the HTSC–PMG levitation part can be further reduced. As PMs are paved along the running line, reducing the PMG cross-sectional area means a large reduction of the cost of levitation. Hence, much effort has been spent in finding a PMG with better cost performance. From the points of levitation efficiency and cost, two PMGs presented in this paper were used to compare with the former 'century' one employed on the first man-loading HTS Maglev test vehicle [10], as shown in table 3. It is noted that the HTS Maglev vehicle is designed to ride on two parallel PMGs. In table 3, the data for the former 'century' PMG is the experimental value and is reported elsewhere [45]. The other two columns' data is deduced from the basic unit experiments by approximate superposition.

By these approximate comparisons, it is found that the levitation efficiencies of the present monopole PMG and double-pole Halbach are both higher than that of the former 'century' PMG. In particular, although the PM cross-sectional area has been reduced to one-third of the first PMG, the bulks above the double-pole Halbach PMG can still achieve almost the same levitation and guidance performance. This improvement means a three-time increase in levitation efficiency or a three-time decrease in the PMG cost, which is exciting for the engineering application. The double-pole PMG with high efficiency magnetic field distribution has promoted the cost performance of the present HTS Maglev system. It makes the HTS Maglev vehicle system closer and closer to practical application.

5. Conclusions

From the point of view of practical application, the performance and cost of an HTS Maglev system with traditional monopole PMG and double-pole Halbach PMG were compared and analyzed in this paper. The static and dynamic experiments show that the seven-bulk levitation unit with the double-pole Halbach PMG can obtain a better load capability, guidance performance, dynamic stability and a better cost performance. From this study, several PMG design conclusions can be reached as follows:

(1) The average magnetic field at applied position will be more important than the peak field.
(2) The optimum PMG configuration is correlated to the performance of the applied bulk HTSCs. They should be matched to each other. Otherwise, the performance of a good material cannot be excited and will be wasted.
(3) The optimal PMG configuration is the function of the gap at which the vehicle is operated.
(4) The double-pole PMG configuration can play an additive important role to the guidance performance of a levitation system due to the potential-well field configuration.
(5) The Halbach PMG has a notable effect in concentrating the magnetic field into its upper surface so as to increase its efficiency and reduce the cost of the PMG.
(6) The homogeneity of magnetic field along the PMG is very important for practical application. As the Halbach PMG cannot homogenize the magnetic field, greater attention should be paid to the precision of each small PM and its assembling precision.

In conclusion, the multi-pole PMG shows some advantages over the traditional monopole PMG at the experimental gap. For practical application, the pole numbers should be designed according to the shape, seed distribution and working gap of onboard bulks. If the HTS Maglev vehicle is designed to run at a large levitation height (over 15 mm) and the precision of each small PM can be guaranteed, the highly efficient Halbach PMG is recommended.

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