This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TASC.2017.2652326, IEEE Transactions on Applied Superconductivity

A Rotational and Straight-line Drive System for Vehicles Levitated Through Superconductor Flux Pinning

J.C. Le Mon, C. A. Baguley, G. Foo, T. Li
Auckland University of Technology, Auckland, New Zealand

***Abstract*—The use of bulk high temperature superconductor material has been proposed for various non-contact transportation systems. Commonly, such systems use permanent magnets to achieve levitation of a vehicle housing bulk superconductors, with motive force provided separately. Recent work has focused on using electromagnets to provide both the levitation, and the motive force. Through energizing appropriately placed electromagnets in a correct pattern, straight line travel and rotation across a horizontal plane are possible. However, significant overshoot and instability can be incurred during motion events, leading to changes in the flux pinning state and misalignment of a vehicle. This paper proposes the design of a planar array of electromagnets and an energization pattern that achieves controlled rotation. Straight line travel is also achieved. Thus, using the proposed drive system, straight-line travel as well as rotation of a levitated vehicle across a horizontal plane is possible. Experimental verification is provided.**

***Index Terms*—HTS, Flux Pinned Levitation, Flux Pinning, Rotation.**

I. Introduction

THE PHENOMENON of flux pinning allows for the suspension of bulk superconductor materials in air, and may be exploited to implement non-contact transportation and servo systems [1,2]. Flux pinning occurs through exposure of a bulk superconductor to a strong magnetic field which, commonly, is sourced from permanent magnets fixed to a surface. Over this surface, levitation of a vehicle housing bulk superconductors may be achieved. A second and alternating magnetic field source may then be utilized to provide a motive force.

While systems of this type are simple to implement, disadvantages exist. Predominant among these is the limitation of vehicle movement in the horizontal plane to the guide path formed by the static and alternating magnetic field sources, when these sources lie on the same surface. This limitation arises because separate static and alternating magnetic field sources placed on the same surface must lie along separate paths that cannot cross. However, recent research has overcome this issue through the use of electromagnets.

In [3-5], superconductor based transportation systems have been proposed that allow for the possibility of horizontal and rotational movement above a planar array of electromagnets. For these systems the levitation and motor drive functions are integrated. Because the guide path can be controlled through the appropriate energization of electromagnets, free movement in the horizontal plane is possible. Further, because the system eliminates mechanical contact and minimizes dust accumulation it is ideal for applications in clean room environments, such as silicon wafer manufacturing and minimally invasive surgery. However, it has been reported that movements occur in a step-like fashion, and that dynamic instability is experienced at the end of each movement step [5]. This limits the potential of the technique for transportation and servo applications.

This paper addresses the issue of dynamic instability during the rotational motion of a vehicle housing superconductors that is levitated and driven above a planar array of electromagnets. It proposes the design of a planar array of electromagnets that are energized in a pattern that significantly reduces overshoot during rotation. Insight into the proposed electromagnet design is given through finite element method (FEM) analysis, and experimental verification of rotational movement is provided.

II. Theoretical considerations

The pinning force experienced by superconductor bulks is governed by [6, 7]:

$$\boldsymbol{F} = \int_V \boldsymbol{J} \times \boldsymbol{B}\, dV. \quad (1)$$

Where, $\boldsymbol{F}$ is the pinning force (N), $\boldsymbol{J}$ is the current density inside the superconductor (A/m^2), $\boldsymbol{B}$ is the flux density (T). Further, $\boldsymbol{J}$ represents the circulating currents set up inside the superconductors in response to the initial pinning field, $\boldsymbol{H}$ (A/m), and is governed by:

$$\boldsymbol{J} = \nabla \times \boldsymbol{H} \quad (2)$$

From (1) it is apparent that $\boldsymbol{F}$ can be varied through changing $\boldsymbol{B}$, causing a flux pinned superconductor to move. This mechanism exists because flux pinned superconductors respond to a change in $\boldsymbol{B}$ by moving to maintain the spatial and angular relationship with $\boldsymbol{B}$ that existed at the time of initial pinning [8]. The manner by which this mechanism is employed for straight line movement is described in Section II A.

1051-8223 (c) 2016 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TASC.2017.2652326, IEEE Transactions on Applied Superconductivity

A. *Straight Line Movement*

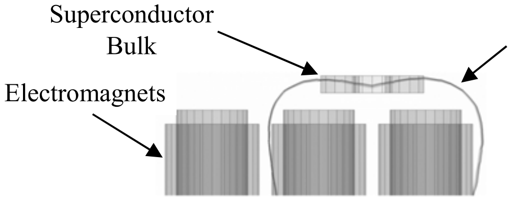

Fig. 1. Cross sectional view of a flux pinned superconductor bulk above an electromagnet plane.

A cross section of a model of a planar array of electromagnets is shown in Fig. 1. The curved line is an isoline indicating points at which ***B*** is 0.1 T, and the arrows indicate the magnetic field direction in the electromagnet cores. Also shown is the superconductor bulk, flux pinned in place. Superconductor bulks pinned at any position along this isoline will oppose any movement that results in exposure to a different value of ***B***.

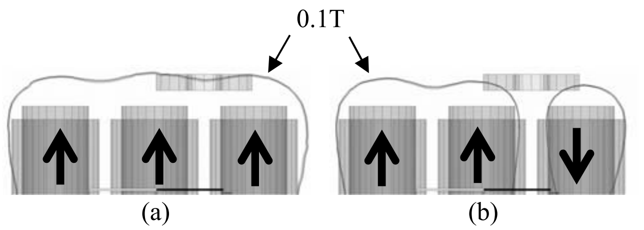

Fig. 2: Magnetic field (a) extension and (b) propulsion to achieve straight-line movement.

To enable straight line movement, the magnetic field must be extended in the direction of travel. Such an extension is shown in Fig. 2(a), and is achieved through appropriately energizing further electromagnets.

To provide straight-line motive force, part of the magnetic field must be altered. This can be achieved by reversing the polarity of ***B*** at the right-most end, as shown in Fig. 2(b). While the polarity of ***B*** is reversed, its magnitude is held constant. This creates a strong repulsive force on the superconductor bulk, pushing it left-wards, where it will be newly constrained.

B. *Rotational Movement*

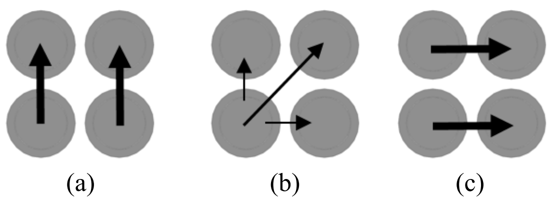

Fig. 3. Magnetic fields for (a), the initial, (b), the transitional and (c), the final states to achieve rotational movement.

Through changing the direction of ***B***, the orientation of a superconductor bulk can be changed, and rotation can be achieved. Vectors representing ***B*** and illustrating this mechanism are given in Fig. 3, which also shows the top view of groups of four electromagnets. If the flux pinned vortices inside the superconductor bulks are unaffected by the rotation process, the pinning force experienced by the superconductor bulk will not change. However, if ***B*** changes faster than the superconductor bulk can rotate, flux vortices will move [9]. Consequently, changes in ***B*** that are too rapid for a superconductor bulk to follow will lead to undesired results. These include a change of the alignment of the superconductor bulk relative to ***B*** and, in an extreme case, ejection of the superconductor bulk from its levitated position above the array of electromagnets. Therefore, the rate of change of current through the electromagnets during the rotation process must be limited. The manner by which this is achieved, and the electromagnet energization pattern used for straight-line and rotational movement, are given in Section III.

III. Electromagnet Configuration and Energization Pattern

A. *Electromagnet Configuration*

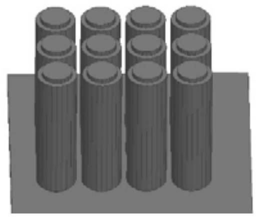

Fig. 4. A 4x 3 arrangement of electromagnets on a mild steel base.

Twelve electromagnets are arranged to form a plane four wide and three high as seen in Fig. 4. A minimum of four electromagnets in a two by two arrangement are required by the superconductor bulk to maintain a particular spatial position. Therefore, the array provides six discrete locations at which a superconductor bulk can stably levitated.

B. *Energization Patterns*

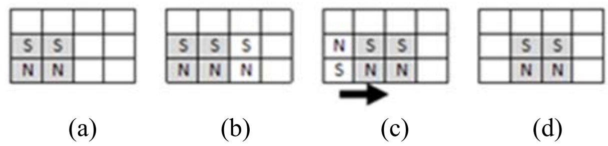

Fig. 5. Energization pattern for (a) the initial, (b) the extension, (c) the propulsion and (d) the final states to achieve straight-line movement.

Fig. 5 illustrates the switching pattern used to achieve straight-line motion of a superconductor bulk. Fig .5(a) shows the initial levitated position, indicated by the shaded portion of the electromagnet array. Fig. 5(b) shows the extended guide path for the vehicle, and Fig. 5(c) shows the moved position of the superconductor bulk achieved by changing the polarity of the leftmost electromagnets.

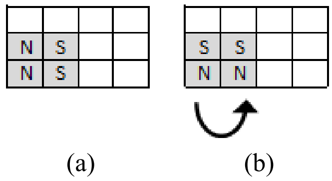

Fig. 6. Energization pattern for (a) the initial and (b) the final states to achieve rotational movement.

1051-8223 (c) 2016 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TASC.2017.2652326, IEEE Transactions on Applied Superconductivity

Rotation of superconductor bulks is illustrated in Fig. 6. Fig. 6(a) shows the initial state in which the superconductor bulk is levitated and stationary. In Fig. 6(b) the polarity has been changed in two diagonally opposed electromagnets, causing the vehicle to rotate. In the transition to the position shown in Fig. 6(b), pulse width modulation (PWM) is employed, as described in Section IV.

IV. Experimental Setup and Results

A. Vehicle Design

Fig. 7. Superconductor bulks in vehicle base in position over electromagnets.

For the vehicle assembly, five superconductor bulks are used. Fig. 7 shows these superconductor bulks inside the containment vehicle with its lid removed. The electromagnet plane is shown underneath the vehicle.

The five superconductor bulks are positioned within the vehicle axisymmetrically about the center position between any four electromagnets. This superconductor bulk arrangement and vehicle design provides a high degree of stability. The superconductor bulks are 14 mm diameter disks, 6 mm thick and manufactured in melt textured YBCO material [10]. The vehicle containing the superconductor bulks is 45 mm x 45 mm x 30 mm (length x width x height), and is 3-D printed in polyamide material [11]. The vehicle lid clamps the superconductor bulks in place with integrated rods. During operation the vehicle is filled with liquid nitrogen and cotton wool is added for insulation purposes.

B. Electromagnet Design

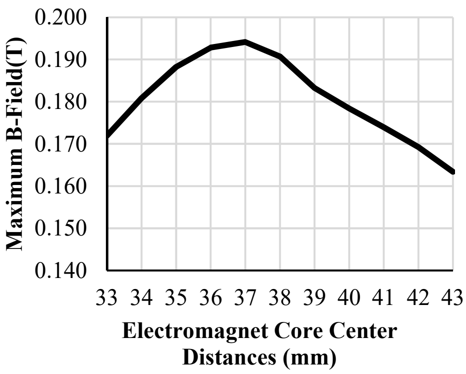

Fig. 8: Plot generated from ANSYS Maxwell modelling showing maximum B field inside the superconductor bulks at a pinning height of 6mm.

Each of the electromagnets have a mild-steel cylindrical core, 25 mm in diameter and 150 mm in length. Each core is wound with 380 turns of 1 mm diameter magnet wire in three layers over a winding width of 140 mm. The electromagnets are spaced at 37 mm center to center. This spacing optimizes the magnetic flux incident on the superconductor bulks at the required levitation height, as determined using an FEM model with the results seen in Fig. 8. The array of electromagnets is placed on a flat base of 20 mm thick mild steel, which reduces reluctance and increases the strength of $\boldsymbol{B}$ above the electromagnets.

Each electromagnet is driven by a dedicated H-bridge, with all twelve H-bridges controlled by a single microcontroller. An Agilent 6572A 20 V, 100 A DC power supply is used to supply the H-bridges [12]. The currents passed through individual electromagnets have peak values of +/- 10 A to generate north and south poles. Further, the current magnitude is controlled through software based PWM. This is used to limit the energy provided during the push phase, as shown in Fig. 5(c), and the rotation phase, as shown in Fig. 6(b). Limiting the current in this manner is essential to avoid instability that can be incurred during a straight-line, or rotation event, and illustrated in Section IV-C.

C. Experimental Results

The initial experiment was conducted with no PWM. Both straight line motion and rotational motion were abrupt and prone to overshoot and, in some cases, led to ejection of the vehicle from the top of the electromagnet plane. Therefore, PWM was introduced. For straight-line motion the PWM was limited to between 5% and 25% duty cycle for the push part of the cycle, as illustrated in Fig. 5(c). This provided sufficient motion with minimal overshoot, while allowing the vehicle to maintain its levitation height. If the PWM duty cycle was reduced below 60% during rotational motion, the vehicle would not have sufficient magnetic field to maintain levitation height. However, if the PWM duty cycle was too high, typically above 90%, the results were indistinguishable from no PWM at all. A PWM duty cycle of 80% was employed and found to be optimal for rotational motion.

Fig. 9 shows the results of rotational motion in the absence of PWM. It is desired to achieve a rotation of 90°. However, at 66 ms the vehicle rotated to 160°, which represents a significant overshoot. Additionally, the final orientation of the vehicle is not the 90° targeted as indicated by the bold line, but 65°, as indicated by the dashed line. This indicates a change in the pinning state of the superconductor bulk, and can be explained by a shift of the flux vortex arrangement, at which the superconductor bulk is pinned.

A change in spatial relationship between an applied magnetic field and a flux pinned superconductor results in a combination of the superconductor moving to maintain that spatial relationship, and a change in the flux vortex arrangement. During the abrupt change in magnetic field after a non-PWM rotation cycle, the vehicle is unable to rotate fast enough to follow the changing magnetic field. Therefore, the flux vortex arrangement inside the superconductors is changed, which gives rise to the off-angle orientation of the vehicle.

The results of limiting the rotational PWM duty cycle to 80% are seen in Fig. 10. This led to a reduction in maximum

1051-8223 (c) 2016 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TASC.2017.2652326, IEEE Transactions on Applied Superconductivity

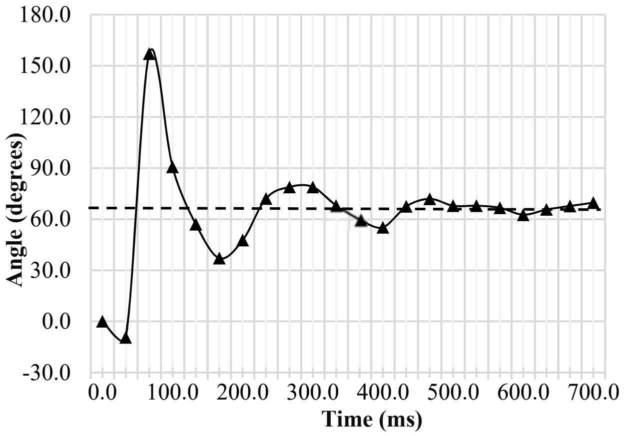

Fig. 9. Rotation Angle vs Time in response to step change without PWM.

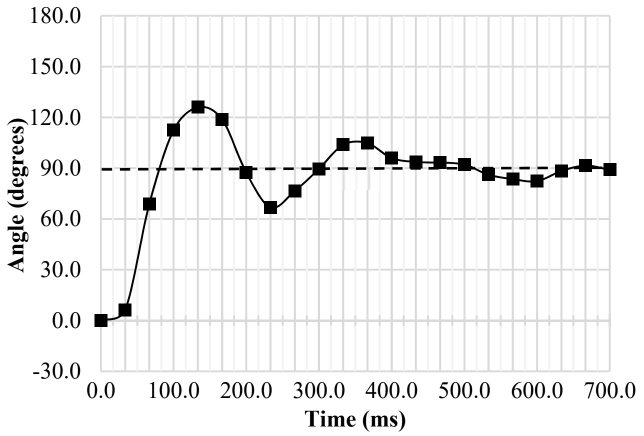

Fig. 10. Rotation Angle vs Time in response to a step change using PWM.

overshoot to 125° and achievement of the target orientation of 90°.

Images of the vehicle before and after rotation are shown in Fig. 11 and indicate 90° rotation of the vehicle. Successful straight-line movement was also achieved.

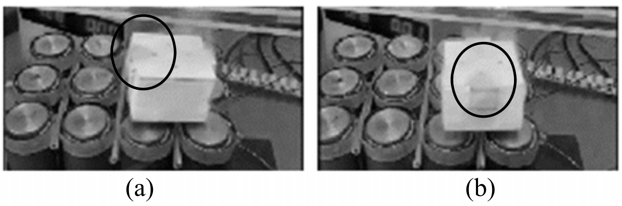

Fig. 11Vehicle before (a) and after (b) rotation. Circles indicate the rear of the vehicle relative to movement.

V. Discussion

The experimental results were obtained using recordings of vehicle motion using a camera capable of recording 30 frames per second (fps). Future experiments would increase this to 100 fps to improve measurements.

In the current vehicle design, the superconductor bulks are arranged to be parallel to the plane of the electromagnets, as shown in Fig 7. However, the incident field on the surface of the bulk may not be aligned to the crystalline structure, due to curvature of the magnetic field lines. As the circulating currents set up in YBCO are anisotropic [8,9], an improvement in the pinning force may be achieved by changing the orientation of the YBCO bulks to align the crystalline structure to be parallel to $\boldsymbol{B}$. This may lead to an increase in the circulating currents from (2) therefore improving the pinning force as per (1).

VI. Conclusion

In this paper a pattern of energization of electromagnets is proposed that achieves straight line motion of a levitated vehicle housing superconductor bulks. This pattern is explained through the use of magnetic isolines, showing how movement is guided. In addition, a pattern of energization of electromagnets for rotational motion is proposed. Experimental results show the effectiveness of the proposed patterns. Further, it is shown experimentally that it is critical to use PWM during motion events to avoid instability, and to achieve a desired motion. Undesired motion can be explained through changes in the flux pinning state of the superconductor bulks. In future, accelerometers and gyroscopes will be added to the vehicle to provide feedback allowing for dynamic control.

References

[1] L. Schultz *et al.*, "Superconductively levitated transport system - the SupraTrans project," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 2301–2305, Jun. 2005.

[2] L. S. Mattos, E. Rodriguez, F. Costa, G. G. Sotelo, R. de Andrade, and R. M. Stephan, "MagLev-Cobra Operational Tests," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, pp. 1–4, Apr. 2016.

[3] S. B. Kim, S. Ozasa, and M. Sawae, "Dynamic Characteristics of a 3-D Superconducting Actuator with Arranged Permanent Magnets and Electromagnets," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, pp. 1–4, Jun. 2016.

[4] S. B. Kim, T. Inoue, A. Shimizu, J. H. Joo, and S. Murase, "Characteristics of a 3-D HTS Actuator with Various Shaped Electromagnets," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 2327–2330, Jun. 2007.

[5] S. B. Kim, H. Nakano, S. Ozasa, and M. Sawae, "Study on the Dynamic Stability of 3-D Superconducting Actuator by Various Typed HTS Bulk Movers," *Applied Superconductivity, IEEE Transactions on*, vol. 25, no. 3, pp. 1–4, Jun. 2015.

[6] G.-T. Ma, J.-S. Wang, and S.-Y. Wang, "3-D Modeling of High-Superconductor for Magnetic Levitation/Suspension Application #x2014; Part I: Introduction to the Method," *Applied Superconductivity, IEEE Transactions on*, vol. 20, no. 4, pp. 2219–2227, Aug. 2010.

[7] E. H. Brandt, "Superconductors of finite thickness in a perpendicular magnetic field: Strips and slabs," *Phys. Rev. B Condens. Matter*, vol. 54, no. 6, pp. 4246–4264, Aug. 1996.

[8] J. H. Durrell, "Critical current anisotropy in high temperature superconductors," 2001.

[9] P. J. Lee, *Engineering superconductivity*. Wiley-IEEE Press, 2001.

[10] "CSYL-14 YBCO Levitation Disk - CAN SUPERCONDUCTORS e-shop." [Online]. Available: http://shop.can-superconductors.com/index.php?id_product=8&controller=product. [Accessed: 16-Aug-2016].

[11] "AUT 3D PRINTING LAB - 3dl," *3dl*. [Online]. Available: https://3dl.aut.ac.nz/. [Accessed: 16-Aug-2016].

[12] "6572A 2000 Watt Power Supply, 20V, 100A [Discontinued] | Keysight (formerly Agilent's Electronic Measurement)." [Online]. Available: http://www.keysight.com/en/pd-839229-pn-6572A/2000-watt-power-supply-20v-100a?cc=NZ&lc=eng. [Accessed: 16-Aug-2016].

1051-8223 (c) 2016 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.