A Multipole Array Magnetic Spring

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***Abstract*— This paper presents research on a magnetic spring concept which has application to the development of a vibration isolation table. Features of the design are scalable, non-contact load bearing and a single degree of instability.**

I. Introduction

Vibration isolation is a requirement for a variety of sensitive equipment, as undesirable vibrations can often cause inaccuracy or error. Commercial vibration isolation tables for cleanroom environments typically use pneumatic springs. It is proposed here that non-contact magnetic springs could be used instead, eliminating the path of physical vibration transmission.

The prior art for levitation tables show designs that are effective vibration isolators, but not well-suited for efficient large load bearing. For example, the design of Mizuno *et al.* [1] is unstable in the vertical direction, and that of Choi *et al.* [2] uses singular magnets which do not scale well with volume.

This paper outlines the design of a non-contact magnetic arrangement that is able to passively bear large loads and is also potentially easily integrated into a control system to remove the inevitable instability elucidated by Tonks [3].

II. Basic magnetic spring design

Two magnets in repulsion create a passive spring force between them. In a vertical arrangement with the lower magnet fixed, the floating magnet is unstable in both horizontal directions. A more stable arrangement is to use three magnets arranged horizontally in attraction, with the outer two fixed and the floating inner magnet acting as the spring element (this is similar in behaviour to an axial magnetic bearing). The floating magnet is stable in the vertical direction and also in the direction perpendicular to the position of the fixed magnets. Diagrams of these arrangements are shown using cube magnets in Fig. 1.

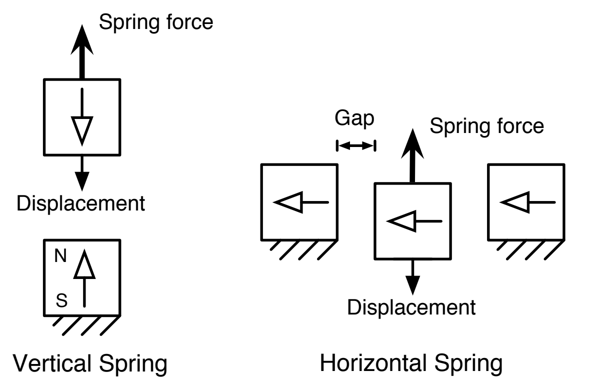

Fig. 1. Schematic of two simple magnetic springs: vertical arrangement in repulsion and a horizontal arrangement in attraction.

The more stable horizontal spring is, however, less appropriate for supporting weight. Graphs of force vs. vertical displacement for these arrangements, solved using Bancel's analytical 'magnetic nodes' technique [4] for 15 mm cube magnets, are shown in Fig. 2. Here the rest position for the vertical spring is 1.5 magnet widths and the gap between the horizontally arranged magnets is 0.1, 0.5 and 1 magnet widths in three separate cases. The weight of the magnets due to gravity is neglected. It can be seen that with the exception of very close horizontal magnet arrangements, the vertical spring may support much greater loads with an exponentially increasing stiffness; furthermore, the horizontal spring becomes unstable if the vertical load is increased past the peak force.

A combination of the vertical spring and the horizontal spring yields a system that is capable of supporting large loads in the vertical direction and is unstable in only a single horizontal direction. This instability may be constrained with passive guides or an active control system with non-contact electromagnetic actuators.

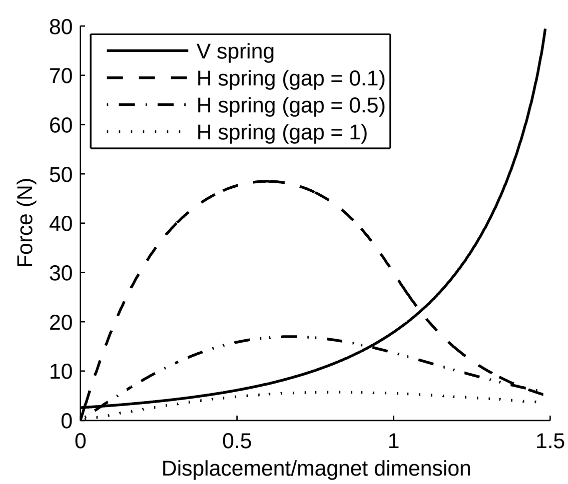

Fig. 2. Force vs. displacement curves for the arrangements shown in Fig. 1 for 15 mm cube neodymium magnets. The gap is normalised by the magnet dimension.

III. Multipole arrays for strength

This 'combination spring' design may be improved by replacing the homogeneous magnets with multipole arrays. Such arrays have been used in magnetic bearings for increased stiffness [5] and their application here follows similar principles. Fig. 3 shows the design of a combination spring that suits the original requirements for stability and load bearing. The fixed horizontal arrays stabilise the spring in the y direction even over a range of vertical displacements corresponding to large variations in the load on the spring.

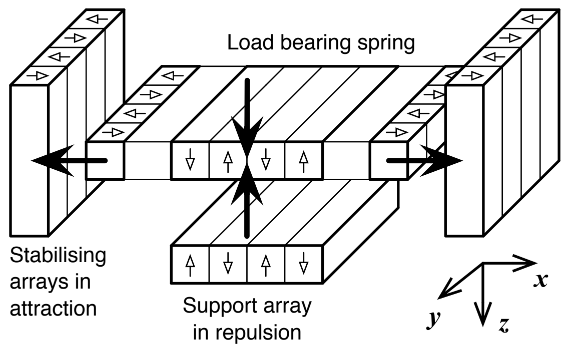

Fig. 3. The complete magnetic spring design with multipole arrays. Solid arrows show the x and z reaction forces on the spring.

To demonstrate the concept, 15 mm thick neodymium magnets are used in a magnetic nodes analysis of the forces on the spring due to displacements in every direction. Each array contains four magnets alternating in magnetisation as shown in Fig. 4. The gaps between the fixed and floating arrays at rest are all equal to the array thicknesses.

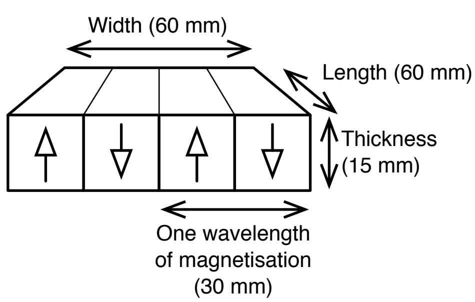

Fig. 4. Geometry of the individual stabilising, support, and load bearing arrays. The wavelength of magnetisation of the multipole arrays is twice their thickness.

A. Load bearing

At rest, the supporting force of this spring is approximately 70 N. Halving the gap increases this value fourfold (see the z direction curve of Fig. 7 later). Increasing the load bearing capacity may be achieved by simply increasing the length and width of the arrays by adding more magnets. The use of multipole arrays provides this scalability without the need to increase the thickness of the arrays.

The magnetic nodes technique restricts the multipole arrays used in this analysis to two magnets per polarisation wavelength, with 180° rotations of magnetisation between successive magnets. Stronger forces than reported here are possible by using 90° magnetisation rotations with four half width magnets or, even better, 45° magnetisation rotations with eight quarter width magnets, in order to accurately approximate sinusoidal magnetisation [6].

A further advantage of using more divisions per wavelength is the focusing effect on the magnetic flux: in the ideal case of sinusoidal magnetisation, the flux is entirely single-sided; but with just two magnets per wavelength the magnetic field is still symmetrical. The absence of leakage flux in the former case removes the possibility of side-effects due to its interaction with other parts of the device.

Another matter to consider is the wavelength of magnetisation. Fig. 5 shows three ratios of magnetisation wavelength to array thickness. As this ratio decreases, the gradient of the force (that is, the stiffness) between two facing arrays increases while acting over increasingly smaller distances. This is shown in Fig. 6 for four pairs of square arrays in opposition. A good compromise between spring stiffness and range can be achieved with a wavelength of twice the array thickness: this ensures a sufficient gap for a range of displacement while still providing a reasonable stiffness.

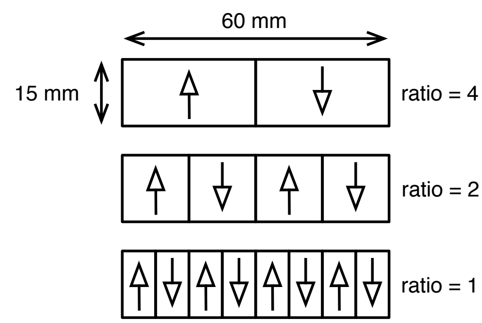

Fig. 5. The cross-sections of the first three variations of magnetisation wavelength to thickness ratio for the curves shown in Fig. 6.

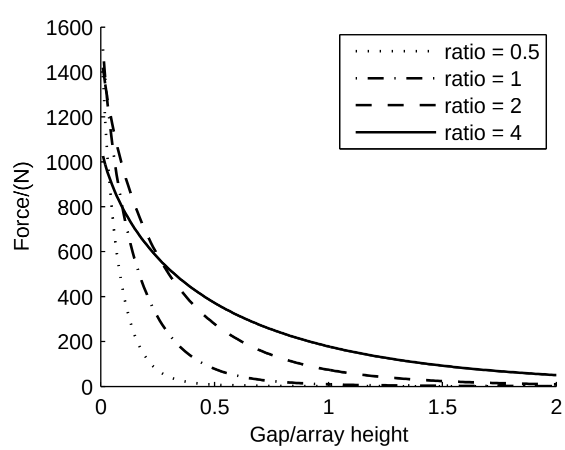

Fig. 6. The forces between opposing multipole arrays for varying ratios of wavelength of magnetisation to array thickness as shown in Fig. 5.

This result is consistent with the analysis of a multipole array levitating against a superconductor [7]. However, there is a notable difference between the behaviour of a multipole array levitating against a superconductor and the behaviour of two opposing multipole arrays.

In the former case, the levitation force is created between the magnet array and a mirror of itself in the superconducting material. Thus, any horizontal shifts of the magnet array are mirrored in the superconductor and the levitation force remains constant. This is a great advantage when using superconductive levitation, but unfortunately the inconvenience and cost of using such material outweighs its advantage for many applications.

In the case with two repulsive magnet arrays, lateral displacements affect the levitation force: a half-wavelength displacement will result in *attraction* between the arrays, compromising the stability of the system (this will be seen in the next section in Fig. 8).

B. Stability of the multipole spring

Fig. 7 shows the forces on the spring due to displacements in each direction. Stable motion requires a negative gradient on these curves, since in this case the reaction force will be in opposition to the displacement. In the centred position, the spring is in unstable equilibrium with instability in the horizontal x direction only. This instability force is quite linear over most of the displacement, which is convenient for control system design.

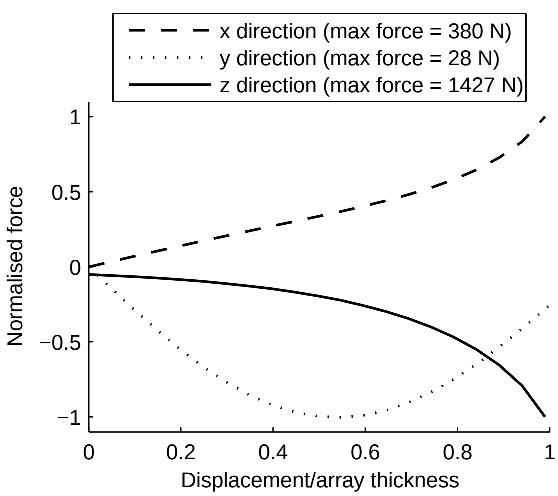

Fig. 7. Forces on the spring in the direction of displacements in each axis. The curves are normalised by their respective peak values (shown in the legend) to display their shape.

The use of multipole arrays limits the displacement of the spring in the horizontal directions, as demonstrated in the y direction curve in Fig. 7. The stability reverses after a displacement of a quarter wavelength of magnetisation as the force-displacement gradient turns positive.

Further disincentive for horizontal motion is the reduction of vertical load bearing as mentioned in the previous section. In Fig. 8, the spring is displaced in the x direction and the graph shows the resultant forces on the spring in each direction. This displacement causes an attenuation of the supporting force in the vertical z direction. Instability occurs as the vertical force turns negative after a displacement of approximately one-third of a wavelength. This is greater than the displacement for instability in the y direction because the stabilising arrays also provide some supporting force.

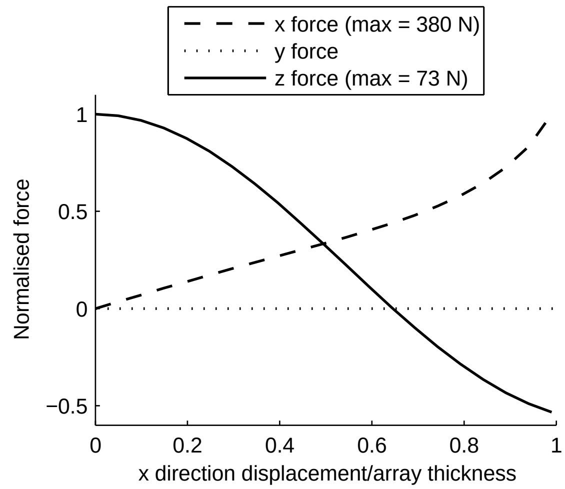

Fig. 8. Normalised forces on the spring in each direction for displacements in the x direction.

IV. Conclusion

The design of a large load bearing magnetic spring has been outlined and shown to have a single degree of instability in its centred position. Significant displacements yield further instability, so the spring must be constrained either by passive guides or an active control system. In this state, the spring may be used as the main support for a vibration isolation table. This latter application is the focus of ongoing research, the results of which will be reported at a later date.

References

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