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Design of a non-contact magnetic spring for vibration isolation

RESEARCH PROPOSAL

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Abstract

This document serves to summarise the research performed by the author undertaken in approximately the first six months of his doctorate. The aim of the project is to build a vibration isolation table using non-contact magnetic springs. The document is structured with an introduction to the project, followed by an introduction to the field of magnetic levitation, including a literature review. The majority of the document then focusses on the basics and findings thus far of the magnetic design of the spring, concluding with the future work and timeline of the project.

Regarding the document

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1 Introduction

This project is a continuation of an Honours project that was completed in 2001. In its inception, the goal of the project was to design a non-contact passive magnetic spring, and develop an active controller for it. The purpose of this was to implement the spring into a vibration isolation table, which could be used to suppress the vibration transmission to a degree higher than that of current vibration isolation tables, which use pneumatic springs. Isolation tables are used for performing experiments which involve highly delicate equipment, such that the natural vibrations from the ground are a source of error.

Not knowing better at the time, it was the inital task of the project to create a passive magnetic spring: a device of some magnetic arrangement that freely levitated, functioning as a regular spring. It soon became apparent that to design a device that passively — or without power input — achieved stable levitation was an impossible task. The reason for this was derived in the famous paper by Earnshaw [1842], which is referenced by the vast majority of all literature dealing with magnetic levitation.

An investigation into the literature has shown that vibration isolation has been somewhat overlooked in the goal to achieve more complicated functionality with magnetic levitation. It will be shown that in general, the papers that deal solely with vibration isolation investigate advanced non-linear control strategies, and those papers which develop advanced magnetic designs do not extend to utilise their design within a highly evolved control system (for vibration isolation). Therefore, this is the avenue that shall be traversed by this project, which has not yet been followed: to design a novel magnetic spring and actuator suitable for a vibration isolation table and incorporate it into a prototype isolation table with advanced control techniques.

1.1 Magnetic levitation is impossible

The act of levitating a magnet by another is well regarded to be impossible, although popular unlearned opinion is not aware of the fact. Samuel Earnshaw wrote a paper in 1842 which proved that objects in the influence of fields that apply forces with an inverse-square relation to displacement cannot form configurations of stable levitation. Since the magnetic field behaves in such a manner, passive permanent magnet levitation is thus impossible.

Approximately one hundred years later, Tonks [1940] wrote a paper consolidating the work of Earnshaw, specialising the proof in the field of magnetics to state quite succinctly that no two separate ‘assemblages’ of magnets could exist with one supporting the other without contact.

However, it has come to light in relatively recent years that there are exceptions to the theorem against magnetic levitations. A proviso stated by Tonks and implied by Earnshaw was that the magnetic fields be *conservative*, or associatively, time invariant. Therefore, a configuration involving the magnetic field generated by a conductor with variable current flowing though it is exempt from the rule.

Also, levitations involving diamagnetic material are not ruled out. As cited by Boerdijk [1956b,a], Braunbek derived that magnetic material is governed by Earnshaw's theorem because it has a relative magnetic permeability (μ_r) greater than one. Material with $\mu_r < 1$ is known as diamagnetic, and is not included in Earnshaw's theorem. Diamagnetic material is repelled by both poles of a regular magnet. Superconducting material can behave ideally diamagnetic ($\mu_r = 0$) and is thus included in this exception.

Finally, there is a childrens toy, known as the Levitron™, which can amazingly defy Earnshaw's theorem. Sold now for over ten years, the Levitron™ is a magnetic spinning top, which, if spun correctly, can stably levitate above a ring magnet. How this can possibly work is certainly non-intuitive, but the physics have been comprehensively verified in two independent papers [Berry, 1996, Simon et al., 1997].

1.2 Exploiting exceptions of the previous subsection

More contemporary studies on diamagnetic levitation looked at the levitation of larger objects including strawberries and frogs [Berry and Geim, 1997, Simon and Geim, 2000, Simon et al., 2001]. Unfortunately, the forces imparted by diamagnets are much too weak to support any substantial load using the magnetic field of even the strongest permanent magnets (those studies used very powerful electromagnets to float even such small objects). The use of superconducting materials do not have this limitation (ie could be used to support larger loads); however, such materials must be cooled with one of the liquid gases to be kept at very low temperatures in order to remain superconductors. Such a requirement infers this method impractical.

It is plainly obvious that a magnetic spring design based on the Levitron is unsuited to the continuous levitation required for any non-trivial task.

Finally, the only exception to Earnshaw's theorem left available involve non-magnetostatic fields in the capacity of active electromagnetic control. The use of active control makes the intention of a passive spring somewhat worthless. It was hoped initially to generate a constant repulsive (suspension) force; with an active system, the suspension force generated is subject to ripples in the current or voltage controlling the levitation. Nonetheless, this is still preferable to the case of a physically coupled system which can transmit ground vibration through direct means into the isolated tabletop. This can be attested by fact that there have been devices capable of nanometre precision which utilised such methods (for example, Kim and Trumper [1998]).

Therefore, while it would be convenient to use a diamagnet arrangement to achieve levitation (since no control system would be required for stabilisation), it is clear that electromagnetic levitation must be utilised in order to design a non-contact spring. Because there have been no useful devices constructed with ordinary diamagnetic material and the use of superconductors is unfeasible for (and thus outside the scope of) this project, further reference to magnetic levitation will be concerned with either passive arrangements (physically contrained) or actively control.

2 Prior art in the field of magnetic levitation

The field of magnetic levitation has been specialised towards several different applications. Two broad subcategories can be identified: research inclined towards using magnetics to make things move, and using magnetics to prevent things from moving. Terminology defined by Kim [1997] distinguishes between these two, naming *levitation* the former and *suspension* the latter.

Clearly, the field of using a magnetic spring for vibration isolation falls into the case of suspension. A short summary of both fields will follow.

2.1 Magnetic suspension: keeping things still

The oldest use of magnetics for actual application was for magnetic bearings. The classic magnetic bearing supports a shaft by applying radially centering forces on the rotor. An example is shown in Figure 1 on the following page. Due to Earnshaw, there must be an instability in the system, which for such a radial bearing is in the axial direction. In the earliest of these bearings, this instability was contained with a physical stop. Backers [1961] developed an early active magnetic bearing (abbreviated as AMB) which used an active control system to stabilise the bearing in the unstable axial direction.

Another application for magnetic suspension is for the support of objects in wind tunnels. Furthermore, a carefully designed system can also measure the forces imparted on the object by the flow in the tunnel. In this manner, an object can be entirely suspended in a flow without the act of measuring and supporting the object changing the interaction the object has with the flowing medium.

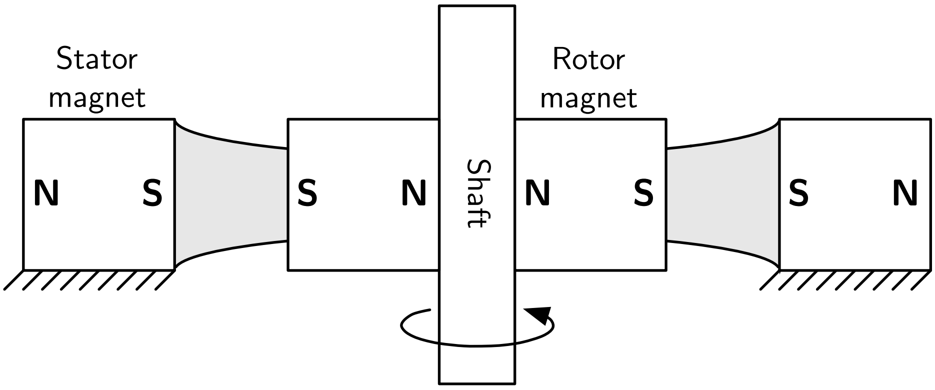

Figure 1: The cross-section of two radially magnetised ring magnets in a radial bearing. Opposite poles of the magnet are labelled N (North) and S (South).

2.2 Magnetic levitation: making things move

The largest and oldest research into magnetic levitation is on so-called ‘maglev’ transportation. Due to its extreme separation to the field in which the author is working, a maglev literature review will be left incomplete.

In more recent years, another application for magnetic levitation has been investigated, which is the precision planar control of a levitated platform. Commonly cited for use in the semiconductor industry for photolithography, these ‘planar active magnetic bearings’ were first researched in the very late 1980s. Such devices are capable of supporting small loads to nanometre precision, and applying translational forces to effect displacements of up to around 200 mm, with similar positioning accuracy. Two such devices are invented in the independent theses of Kim [1997] and Molenaar [2000]. These two authors have contributed significantly to the literature on this topic.

2.3 A note on terminology

Of quite considerable variety is the terminology used for the different topics and devices investigated by researchers in magnetics. While for this paper the terminology used by Kim has been adopted to describe levitation as making things move and suspension to keep them still, this separates into the two groups the fields involving active magnetic bearings and *planar* active magnetic bearings. It is the opinion of the author that, while initially disconcerting, this separation should be encouraged. It is due to a blurring between the two groups that some authors have assigned the name ‘rotor’ to the floating element used in planar AMBs, when of course this element is not intended for rotation! The substitutions 'flotor'[1] and 'platen' are suggested in literature, with the latter more popular. The author prefers neither, but has not yet decided how to describe the as yet un-named object in question.

2.4 Literature review of relevant articles

While it could not be said that the use of magnetic levitation for vibration isolation is a novel concept by itself, there is certainly a dearth of literature on the subject. Many papers that are of possible interest to the research have been exclusively published in Japanese or Chinese, and among the Western papers, few have dealt with the vibration isolation of large loads.

A paper which most simply demonstrates that magnetic springs can be used for vibration isolation is Puppin and Fratello [2002], in which the authors make no attempt for contactless suspension; the magnets are horizontally constrained in guides. Furthermore, the springs are only used as passive isolators for vibrations in the vertical direction; no active control is used.

Nagaya et al. [1993] constructed a vibration isolation table to demonstrate their superior control method; they report a high-stiffness spring with transmissibility approaching zero. However, their table only used small magnets in a simple design, which could not support large loads. According to Yonnet et al. [1991], simply scaling magnet volume to increase load bearing is inefficient; it is the opinion of the author that a practical large-load spring must be fundamentally different than the one used by Nagaya et al..

Watanabe et al. [1996] wrote a paper detailing a functional vibration isolator using electromagnetic springs, which could support weights of up to 200 kg. The control system used was quite advanced, utilising a combination of PI control for and stable levitation and H^∞ control for vibration isolation. The magnetic actuator design is not described, and it is the opinion of the author that while the control system is very advanced and performs well, the power that must have been dissipated by the electromagnetic coils makes this design inefficient in this respect.

More recently, Choi et al. [2003] have designed a levitation table unstable in only one degree of freedom. However, the magnetic arrangement used for the spring, despite their claims, appears quite unstable. Their experiments prove that only a single axis requires control for stability, but the position resolution they achieve is very coarse. In the same way as Nagaya et al. [1993], it is also unsuited for scaling to bear larger loads.

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[1] A possible reason for the unpopularity of this term could be the excretion connotations which it evokes

A novel design for achieving an infinite (theoretically) stiffness spring is outlined by Mizuno et al. [2003]. By using physical springs in series with electromagnetic suspension springs, three degrees of freedom of an isolation platform are actively controlled, with the total weight supported around 30 kg. The achievement is ingenious, but, like the others, uses a most simple electromagnetic spring design, which could not be scaled significantly to support larger loads.

3 Design of a magnetic spring

This section will deal with basic macroscopic concepts in magnetics, and some of the methods which may be used in the design of a magnetic spring for this project.

3.1 Goals of the magnetic design

The design of the magnetic spring has the following requirements:

1. One degree of freedom instability:

   Every unstable axis requires actuators for stability control. Therefore it is desired to minimise the number of unstable degrees of freedom. Furthermore, the unstable direction must be in the horizontal direction for efficient passive vertical load bearing.

2. Ability to support large loads:

   It is desired for the entire weight of the table plus equipment be supported by the permanent magnets. Weight supported by electromagnets consumes large amounts of power, which is undesirable for cost and heat reasons.

3. Effective electromagnet actuator placing:

   Actuators which apply forces unsymmetrically will apply a moment to the levitating table, which would be undesirable. Electromagnetic actuators must be used for stabilising the unstable axis as well as for rejecting vertical disturbances.

3.2 Permanent magnet design

It is the purpose of this section to ignore the reasons for the magnetic field or any complex equations relating to magnetics, but rather develop an informal understanding of magnetic behaviour.

Firstly, it is stated for completeness that a magnet has two poles: North and South. Two magnets placed with opposite poles facing will attract each other. Conversely, two magnets placed with like poles facing will repel each other. That these forces occur is very well know, but the mechanisms that create these forces is beyond the scope of this document.

There are several materials of which permanent magnets may be made. Short attention will be placed on the cheaper, legacy magnetic materials. These, such as the ferrite magnets and alnico magnets, have weak magnetisation such that they may be demagnetised by strong magnetic fields. Rare earth magnets have been available for the last twenty years, which have much more desirable properties than these old fashioned magnets.

The most simple example of a magnetic spring can be demonstrated by two disc magnets in a tube, or two ring magnets on a shaft, as seen in Figure 2 . With unlike poles facing, the magnets repel each other and generate an air gap between them. Displacement towards each other is restored by the repulsive force, and displacement away is restored by gravity.

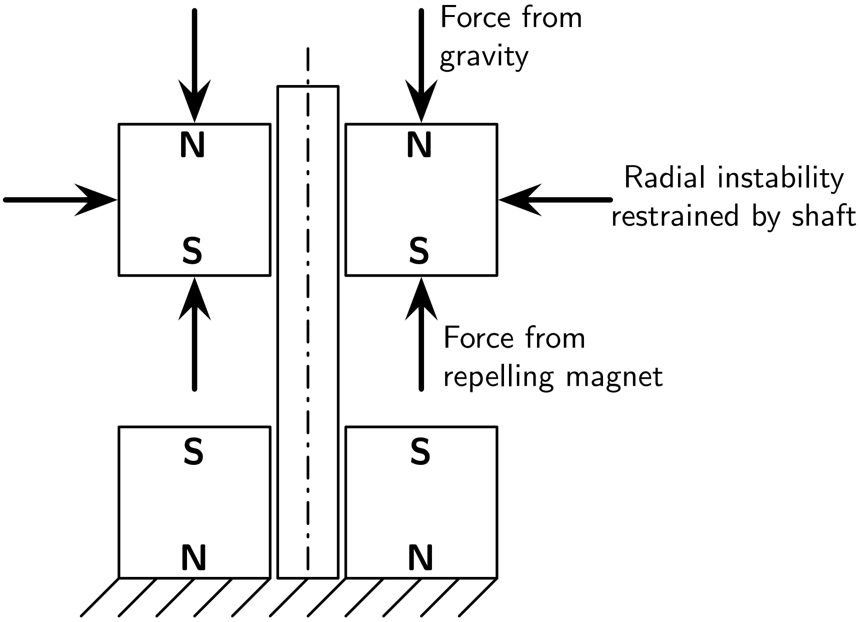

Figure 2: The cross section of a basic magnetic spring, shown with restoring forces on the suspended body

Recall that the aim of the project is to develop a contactless spring; the instability will be corrected with electromagnetic actuators. If the shaft is removed from the simple spring (recall as shown in Figure 2), it will be unstable, naturally. The magnet will tend towards horizontal motion, resulting in instability in the two orthogonal horizontal axes. A more controlled (but no less unstable) way of arranging two magnets is shown in Figure 3 . This arrangement is known as a thrust bearing, and has the advantage in that if instability does occur, the unstable magnet will not fly unpredictably away from the fixed magnet (because the former will be constrained by the latter).

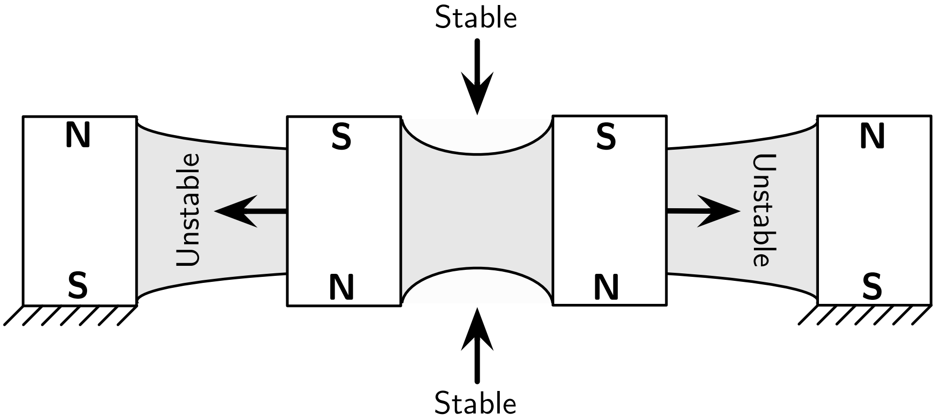

Figure 3: A cross section of a 'thrust bearing'. Note that this has the same behaviour as the spring shown in Figure 2 on the previous page

Looking towards a design which can be used as an efficient spring: a similar configuration to the thrust bearing can be arranged with bar magnets, which is unstable only in one direction. This configuration can been imagined as having the same cross section of a thrust bearing (Figure 3), albeit the floating magnet is stable in the plain of the page (which in the thrust bearing is not, because of radial symmetry).

This design forms a possible basis for the first requirement of the magnetic design (only one unstable axis, in a horizontal degree of freedom). It is certainly a simple design.

The next goal required for the design of the magnetic spring is high load capacity. Yonnet et al. [1991] show in their paper that there is a more efficient way of scaling magnetic designs than simply increasing the volume of the magnets. The work in this paper is significant and will be described subsequently.

Earlier, Yonnet [1978] proved that the forces between radial bearings are equal regardless of whether they are axially magnetised or radially. (To be precise, the forces exerted by two magnets upon each other remain equal so long as the sum of their angles of magnetisation remain constant.) So, for example, the two bearings shown in Figure 4 , despite having different magnetisation directions, have the same stiffness (due to the forces being equal). His later paper [Yonnet, 1981] continues this work to describe every possible simple axial and radial spring, for both axial and radial directions of magnetisation.

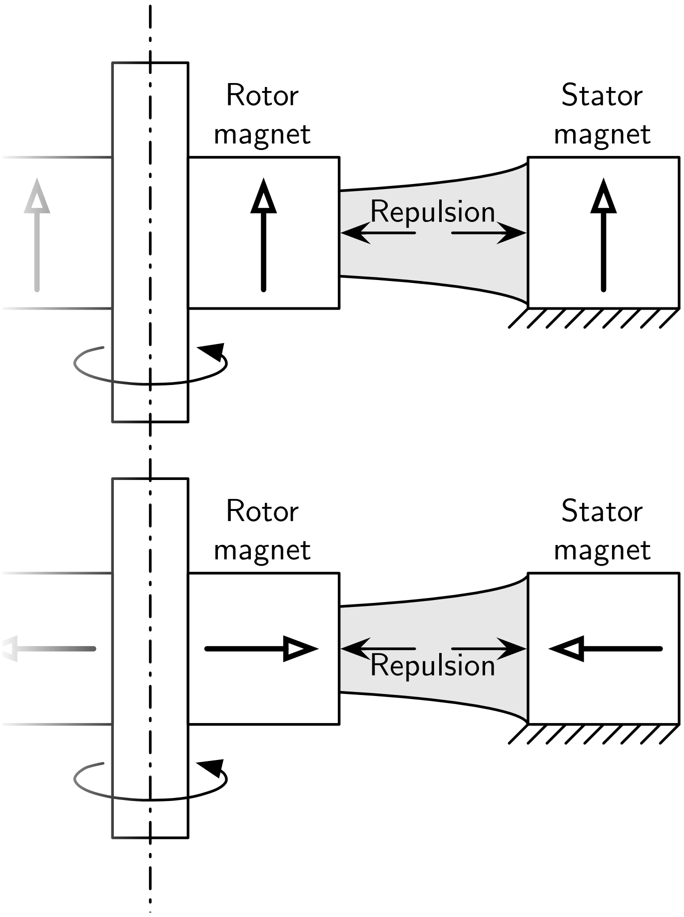

Figure 4: Two equivalent radial bearings (with equal forces of repulsion), despite their different directions of magnetisation (indicated by arrows instead of labelling the poles, whereby the head of the arrow is at the north pole of the magnet).

It was found [Yonnet et al., 1991] that by stacking such equivalent bearings together (in example, Figure 5 on the following page), a much greater stiffness *per volume* was achieved. Their work was based around developing a stiff radial bearing, which is not dissimilar to a vertical spring.

The use of these stacked magnets stems from the work of Halbach [1980, 1981] on multipole magnets. While his purposes were radically different, he found that arranging magnets with rotating magnetisation directions concentrates the magnetic field on one side of the stack, and reduces it on the other. This has the effect of 'focussing' the flux into the areas where it is inferring forces, creating a magnet that is predominantly single-sided. These stacks are sometimes known as Halbach arrays.

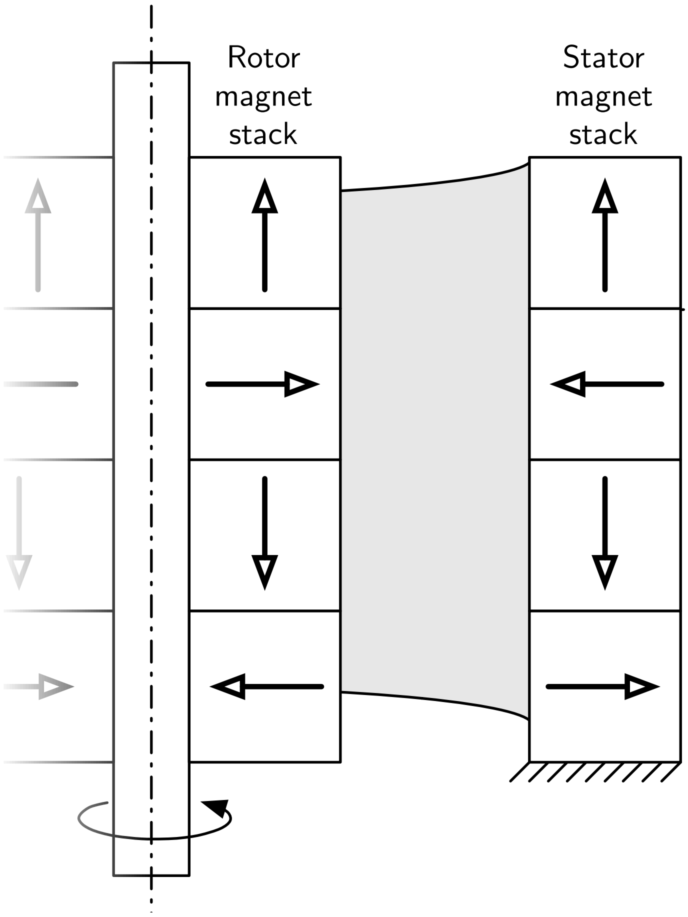

Figure 5: By stacking equivalent bearings as shown, a greater stiffness per volume can be achieved than for a magnet configuration with a single direction of magnetisation.

The work of Yonnet et al. [1991] deals with only one-dimensional Halbach arrays, which may be termed *linear arrays.* Kim [1997] in his thesis developed a 2D Halbach array (similarly, *planar array*), demonstrating that the benefits gained (for the purposes of levitation) from stacking one-dimensionally can be extended to planar stacks.

It is proposed at this stage to incorporate these planar arrays in a one-degree of freedom unstable (horizonatally) spring, shown in Figure 6 . This will form the basis of the spring itself.

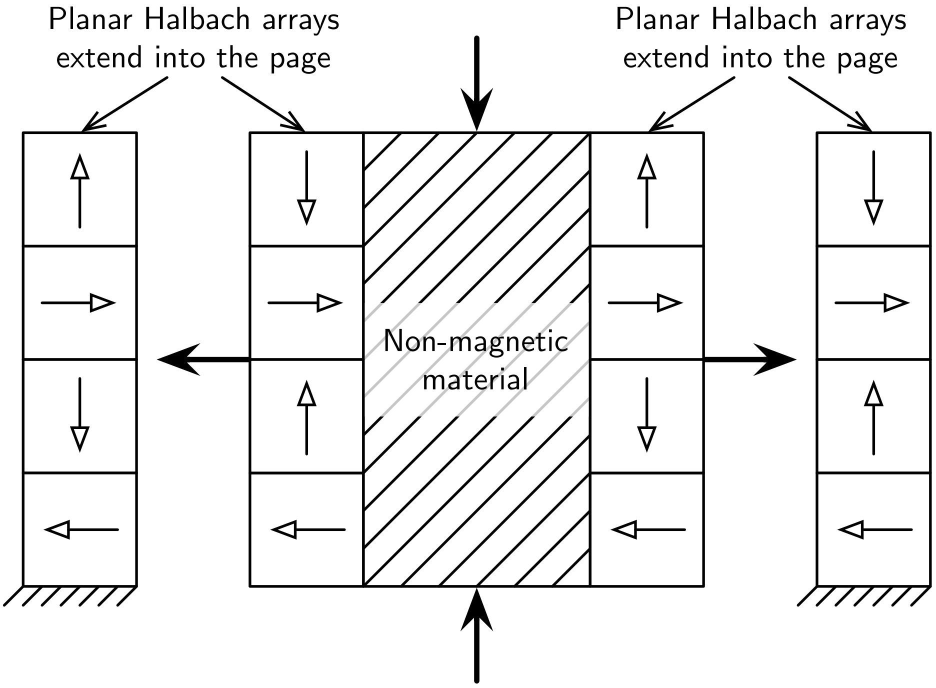

Figure 6: Cross-section of the proposed non-contact magnetic spring design. Note that the ‘flotor’ is attracted to both sides of the ‘stator’ and is thus unstable in the horizontal direction, but stably supported in both the vertical and into-the-page directions.

A number of questions need to be answered before a final prototype model is constructed. It has been proposed to construct a magnetic spring with the two supporting magnets placed on the side of the floating magnet, rather than below. The first question is whether this is a suitable arrangement. There is a possibility that a significantly greater stiffness could be achieved by placing the supporting magnets directly below the floating magnet, in direct opposition to gravity. This will be answered in the coming months with theoretical analysis, FEA modelling, and experimentation.

3.3 Electromagnetic design

The third requirement of the spring design involves how coils will be used to apply electromagnetic forces on the spring. Two separate functions are needed: stability of levitation, and rejection of vertical disturbances. These two forces will act orthogonally on the spring.

Electromagnets behave in some ways like permanent magnets. A current flowing in a wire will produce a magnetic field, and the shape of the wire windings will determine the overall shape of the produced magnetic field. A solenoid (or coil) carrying a current, for example, will produce a magnetic field equivalent to that of a permanent bar (or cylindrical) magnet. This is represented in Figure 7 .

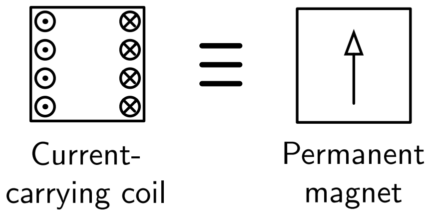

Figure 7: Demonstrating the equivalence of a coil and a magnet

The strength of the magnetic field created by an electromagnet increases with current. An object in the vicinity of such a field field will have a force inferred upon it, which may be varied by altering the current. By placing a coil next to a magnet and adjusting the forces that are applied to it, Earnshaw's theorem may be denied.

It has been shown by Kim [1997] that a coil may be wound to simulate a Halbach array, in that the magnetic field produced is predominantly one-sided. It is proposed that, to control the vertical vibrations of the spring, an additional planar Halbach array be used on the underside of the spring, with a Halbach electromagnet below to provide the necessary actuation.

The spring must also be modified to include the necessary actuation for stabilisation. This must still be investigated to determine the optimal placement, but a possible complete design is shown in Figure 8 on the next page.

4 Control systems

The control systems that will be used for the magnetic spring, as well as for vibration isolation, have not been investigated by the author.

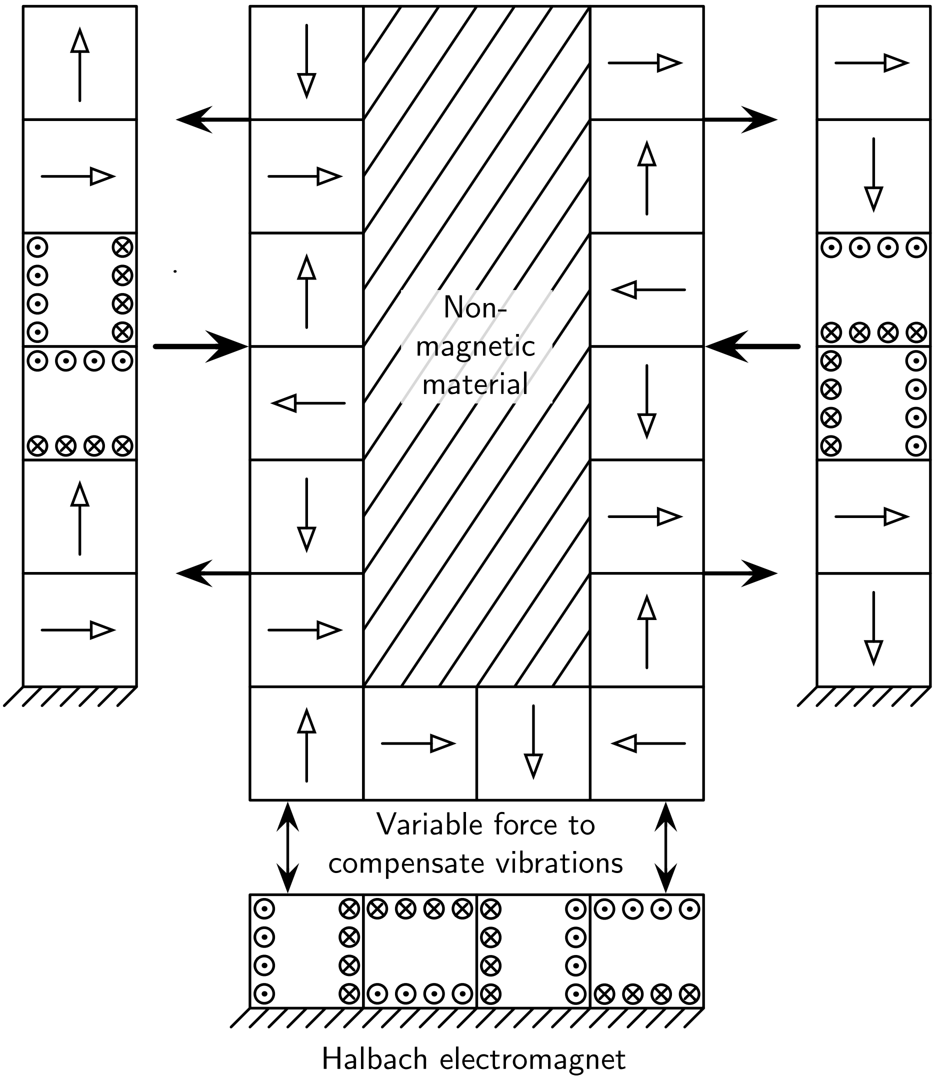

Figure 8: A conceptual complete design. The instability of the magnetic spring is counteracted upon by the electromagnets in the sides, while the vibration isolation is performed by the Halbach array below.

The behaviour of the magnetic spring will be highly non-linear in all aspects; as the spring deflects, its stiffness will change. Therefore, as different loads are placed upon the table, the control system will have to adapt itself in order to compensate.

Further work on this section will be undertaken closer to the implementation of a prototype.

5 Project timeline

The research has been projected to last three years, this paper marking the first deadline at six months. The next six months will be spent experimenting with and finalising the magnetic spring and actuator design, on which a journal paper will be written. A prototype spring will be built, and a control system designed for the purposes outlined previously. This is scheduled for completion, and a journal paper written regarding it, in the second half of 2004. 2005 will be spent constructing a full-scale vibration isolation table based on this work, and the writing of the thesis will finish the project in early 2006.

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