On the robustness of flux feedback control for electro-magnetic Maglev controllers

This item was submitted to Loughborough University's Institutional Repository by the/an author.


Additional Information:

• This conference paper was presented at the 16th International Conference on Magnetically-Levitated Systems and Linear Drives (MAGLEV 2000), Rio de Janeiro, June 7-10.

Metadata Record: https://dspace.lboro.ac.uk/2134/5077

Version: Published

Publisher: © Roger M. Goodall

Please cite the published version.
This item was submitted to Loughborough’s Institutional Repository (https://dspace.lboro.ac.uk/) by the author and is made available under the following Creative Commons Licence conditions.

For the full text of this licence, please go to: http://creativecommons.org/licenses/by-nc-nd/2.5/
On the Robustness of Flux Feedback Control for Electro-magnetic Maglev Controllers

GOODALL, Roger M
Department of Electronic & Electrical Engineering
Loughborough University
Loughborough
Leicestershire
LE11 3TU, UK
Tel: +44 1509 227007
Fax: +44 1509 227008
Email: R.M.Goodall@lboro.ac.uk

Abstract

The paper presents a theoretical study of three different forms of magnet control for Maglev vehicles (voltage, current and flux density), in particular to analyse the effect upon the stability and robustness of the overall suspension control. The analysis demonstrates the superior performance of flux feedback control, not only in terms of the basic stability margins, but also the robustness to the parametric variations associated with the inherent non-linearity of the electro-magnetic scheme. Practicalities of implementation for flux control are also discussed.

Keywords: Maglev, flux control, robustness

1. Introduction

Although a variety of controllers for electro-magnetic Maglev suspensions have been successfully implemented, based invariably upon a measurement (or estimation) of airgap, the issue of different types of inner loop feedback (i.e. to provide primary control of the magnet itself as opposed to the suspension) has not been rigorously explored. It is generally recognised that having no inner feedback, i.e. simply controlling the magnet voltage, is not a satisfactory option, and most workers use a fast-acting inner current feedback to give current control (usually implemented within the magnet power amplifier) [1, 2]. However a small number of applications have exploited flux control [3], for which a number of benefits arise, and it’s also worth emphasising that similar benefits arise when flux control is used for active magnetic bearings (AMBs) [4].

This paper makes a comparative study between the three magnet control options: voltage control, current control and flux density control. It examines the effect of these three approaches upon the main airgap control loop in terms of basic controllability (i.e. the range of bandwidths which are possible), the stability margins, and the robustness.

Since the main message of the paper is the superior performance of the flux feedback control option, implementation aspects are included: how to measure the flux density in practice and what the associated signal conditioning consists of.

2. Modelling

The analysis is based upon a 1 tonne levitation magnet with a nominal airgap of 15mm working at a flux density of 1T, requiring 20kAT of excitation with a nominal current of 10A. The coil resistance has been determined by assuming copper windings with a current density of 3A/mm² and a packing factor of 0.7. A leakage inductance of 5% of the mutual inductance (i.e. the inductance via the rail) is assumed. Because the assessment is based in the frequency domain it is necessary to use a linearised model, and the parameters of the model are expressed in terms of the nominal values of current, flux, airgap etc so that an appropriate combination of parametric variations can be assessed. Rather than changing individual linearised model parameters in an unstructured manner, it is possible for example to assess what happens with a different nominal airgap, in which case a number of the model parameters vary together, giving a more realistic assessment of robustness.

2.1 Basic electro-magnet model

The linearised model is shown in Fig. 1, in which $K_I = B_a / I_a$, $K_g = B_g / G_a$, and $K_x = 2F_x / B_a$, where $I_a$, $G_a$, $F_x$, and $B_a$ are the nominal values of current $I$, airgap $G$, force $F$ and flux density $B$, respectively. Lower case letters are used to indicate small variations around the nominal values. $V = V_0 + v$ is the magnet input voltage. (See reference [5] for the derivation.)

2.2 Parameters and dynamic characteristics

The other parameters and their values are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance $R$</td>
<td>10</td>
</tr>
<tr>
<td>Leakage inductance $L_a$</td>
<td>0.1</td>
</tr>
<tr>
<td>Poleface area $A$</td>
<td>0.001</td>
</tr>
<tr>
<td>Suspended mass $M$</td>
<td>1000</td>
</tr>
</tbody>
</table>

[Ω]  [H]  [m²]  [kg]
This can be converted into a state space model for analysis in Matlab, as follows:

\[
\begin{bmatrix}
0 & 1333.3 & 20000 & 0 \\
1 & 0 & 0 & x + 0 \\
0 & 0 & -100 & v \\
1 & 0 & -0.001 & 0 \\
0 & 0 & 10 & x \\
0 & 0.0667 & 1 & f
\end{bmatrix}
\]

(NB this state-space formulation has been produced by Matlab from a Simulink diagram, and so the states x are arbitrary.)

The eigenvalues of the magnet model are 36.5 rad s\(^{-1}\), -36.5 rad s\(^{-1}\), and -100 rad s\(^{-1}\). These show the well-recognised instability in the form of a pole with a positive real part, the associated negative pole and a third pole corresponding to the electrical circuit. The cause of the instability is the overall positive feedback around the inertial loop via the linearised coefficient \(K_p\) as shown in Fig. 1.

3. **Control loop analysis**

The principal aim is to achieve stable airgap control with an appropriate bandwidth. From a suspension point of view it is valuable to have a choice of bandwidth: a low bandwidth will provide some attenuation of the track irregularities as the vehicle moves along, whereas a high bandwidth might be chosen to give rapid reaction to counteract the effect of load changes, for example, although too high a bandwidth will tend to cause difficulties with flexible modes in the vehicle structure. Of course more advanced control structures are possible to achieve a more sophisticated suspension controller (eg [6,7]), but many of the attributes provided for a straightforward airgap controller by a careful choice of inner loop also apply to those more complex control structures.

The use of inner feedback loops is a classical control technique, the practical advantages of which have been recognised by control engineers for many years, although the advent of so-called modern control techniques has tended to reduce their use. In general it is possible to achieve an inner loop bandwidth which is significantly higher than that possible for the main feedback alone, and this has the effect of enclosing some of the dynamic elements, effectively reducing the dynamic complexity of the main loop and thereby facilitating its design. The difficulty is choosing what is the most appropriate inner feedback variable: current is an obvious choice for a Maglev controller, but the other possibilities are flux density and force. In many senses the effect of the last two is quite similar, but the measurement of magnet force requires special instrumented mounting brackets and is not therefore straightforward – hence the interest in using flux density, although care is still needed to achieve an effective measurement, as described later in the paper.

The design and stability of the airgap loop, including the effect of the closed inner feedback loop, is assessed in the following subsections using a Nichols chart, which is a convenient means of displaying stability margins and bandwidth in a single diagram. The gain of the airgap loop \(G\) is designed to give as high a bandwidth as possible, assisted by a phase advance compensator to provide an adequate phase margin (\(>40^\circ\)). The phase advance compensator is represented by the transfer function \((1 + k\tau)/(1 + s\tau)\), in which \(k\) is the phase advance ratio and \(\tau\) is the time constant.

3.1 **Voltage control**

Voltage control of course involves no inner feedback, and the basic control loop for analysis is therefore as shown by Fig. 2. This is a difficult loop to stabilise, in part because the open-loop phase increases beyond \(-180^\circ\) due to the magnet inductance. In addition, the open-loop instability forces a minimum value of control gain to achieve stability, essentially so that the airgap feedback is sufficient to overcome the inherent destabilising effect. Once stability has been achieved the loop bandwidth is inevitably high. The lowest bandwidth is around 20Hz, achieved with \(G = 15\) V/mm, \(k = 10\) and \(\tau = 3\)ms, although this results in a loop with inadequate stability margins, as shown by the Nichols chart in Fig. 3. The conditionally-stable response, a phase margin of only 20\(^\circ\) and a gain margin of 7dB mean that this will be a most unsatisfactory controller, and reinforces the general expectation and practical experience that voltage control for Maglev magnets is not a good option. It nevertheless provides a baseline by which the other two control options can be assessed.

3.2 **Current control**

Fig 4 shows the addition of an inner current control loop. Some researchers ignore the current loop dynamics and use a model with current directly as an input, which is generally a good approximation because a high bandwidth can easily be achieved, usually built into the power amplifier. However for this paper a proportional plus integral (PI) compensator has been included to give an inner loop bandwidth of about 50Hz. The Nichols chart for the corresponding airgap control loop can be seen in Fig. 5. Again the inherent instability results in the open loop response having a limited low frequency gain, in this case +8dB at \(-180^\circ\). An airgap loop gain of 1500A/m has been used with a phase advance having \(k = 5\) and \(\tau = 6\)ms. The response is still conditionally-stable, as with voltage control, but the current feedback has enabled much improved stability margins to be achieved. However again the bandwidth is forced to a high value, here around 20Hz, and there’s nothing that can be done to reduce this value.

It is possible to add an integral term in the controller at low frequency, but this will inevitably deteriorate the
stability margins, in particular because the conditionally-stable nature of the loop is aggravated (the gain at low frequencies is increased, but the phase starts at -270°). In some circumstances this may be a sensible thing to do, but in general it does not significantly help in controlling the loop bandwidth.

3.3 Flux control

Fig. 6 shows the system with an inner flux loop; again a PI compensator has been employed within the inner loop to give a flux loop bandwidth of 50Hz. In this case the Nichols chart of the airgap loop (Fig. 7) looks quite different, principally because the destabilising effect of the airgap coefficient Kg is now enclosed within (and overcome by) the rapidly-responding flux loop, and the characteristic is approximately a normal type 2 system response. A gain of 20T/m combined with a phase advance compensator chosen to have values of $k = 5$ and $\tau = 20$ms gives a 10Hz bandwidth for the loop, although it is easy to achieve a lower bandwidth if required because the loop is no longer conditionally stable.

With flux control the fundamental magnet instability is therefore overcome in a different way, not by the airgap feedback but by the inner flux loop, essentially creating a neutrally-stable force-based control which the airgap loop can readily convert into an appropriate suspension response.

3.4 High bandwidth problems

Generally of course control engineers are looking to achieve high bandwidths, and so it's useful to clarify why the previous sections has portrayed the much more controllable bandwidth achievable using flux feedback as an advantage. The difficulty with voltage and current control is that of being forced towards a higher bandwidth than required: amplification of sensor noise induced by the power amplifier is one problem, and also saturation limits are reached much more quickly with the high gains needed to achieve stability. However the most profound problem is that of structural resonance, an effect which appears in most practical examples of high performance control of mechanical systems, because the flexibility of the mechanical structure is almost invariably de-stabilising, and either a lower gain or the introduction of a "notch filter" is needed. The other option is a stiffer structure of course, but this is often impossible without a large weight penalty.

4. Robustness analysis

The non-linearity of the electro-magnet's equations mean that there will be substantial changes in the parameters of the linearised model as it moves through its operating range, and it is therefore essential to investigate the effect upon the suspension response. Here this has been carried out by considering two variations in the steady operating position - a different airgap and a different load. The effects on both the open-loop frequency response and upon the time responses are presented. The robustness analysis has been restricted to assessing the current and flux control options.

The effects of parametric variations in the magnet are assessed by considering two cases. The first uses fixed load mass, but with the nominal airgap $G_0$ varied from 10-20mm. $I_1$ will of course have to change in proportion to $G_0$ (to a first approximation) in order to keep the flux density constant. The second case uses fixed airgap $G_0$, but varying the load mass $M$ from 750-1250kg. The square law relationship between the flux density and force means that the flux density will vary between 0.85 and 1.12T, and the nominal current in proportion to this.

Figs 8 and 9 compare the Nichols charts for current and flux control - in each case there are three graphs representing the minimum, nominal and maximum values of $G_0$. There are substantial variations in the response for current control, although the response remains stable, whereas for flux control the three conditions result in almost exactly the same response (a careful look will reveal small variations in the high frequency region). The fast-acting flux loop essentially absorbs the parametric variations, something which does not happen with current control because the variations occur outside the current loop.

Figs 10 and 11 give the corresponding responses for variations in mass $M$. Again there are significant variations with current control, and in particular the conditionally-stable point on the graphs is moved. The effect on the response with flux control is noticeable this time because the parametric variations occur outside the flux loop, but there is very little impact upon the stability margins.

Fig 12 shows the time responses for the current and flux controlled systems with varying load mass; there are two sets of three responses, one set for each control option and the three graphs in each set corresponding to the minimum, nominal and maximum values of mass. The graphs are step responses for a 1mm change in airgap command. For flux control there are some changes in the transient response as the mass varies, but these are relatively minor. By contrast, with current control, there are substantial effects, in particular because the steady-state value, which in any case does not correspond to the 1mm command, alters as the mass is varied.

5. Practical issues for flux control

The previous sections have identified clear advantages of using flux control from a theoretical viewpoint, and the author's experience of a variety of Maglev system examples, including one AMB application, has confirmed that the theory predicts - a controller which is easy to design and commission, and one which is robust in operation. There are however a number of issues relating to achieving flux control in practice which need to be appreciated, and these are described in the following sub-
sections. The comments should help anybody wishing to perform practical experimentation of the ideas.

5.1 Sensing

The most obvious solution is to use a Hall effect device because it directly gives a measurement of flux density. The difficulty is that it has to be fitted in the airgap, which effectively reduces the operating airgap (or requires increased magnet size to keep the same airgap). Putting the sensor in a hole in the magnet poleface is not a solution because the majority of the flux density simply bypasses the hole, leaving very little of the mutual flux density measured by the sensor.

The other approach is to use a search coil; this can be wound either around the tips of the poles or onto a small steel core fitted into a hole in the poleface, or embedded into a machined slot in the poleface. The author's experience of the first approach is that the coil picks up substantial effects from the leakage (i.e., non-mutual) flux, resulting in a poor performance. Usually the last option is best, but this depends upon the particular application, and either the second or the third approach results in a satisfactory measurement. It's worth noting that the measurement is really concerned with estimating dynamic changes in force; since there is a square law relationship between flux density and force, the ideal would be to measure the r.m.s. flux density over the poleface, whereas the search coil measures the average over its area. A larger search coil gives a greater measurement sensitivity, but includes a wider distribution of flux density and therefore a less appropriate measurement. Experience suggests that a search coil which covers a relatively small part of the centre of the poleface, somewhere near the point of greatest flux density, provides the most effective measurement, even though the sensitivity is reduced.

5.2 Search coil integrator

The signal from the search coil needs to be integrated to produce a flux density signal, but of course a pure integrator is not practical. Consequently it is necessary to incorporate a high pass filter to reject the low frequency drift, and the combination of the integrator and a second order Butterworth high-pass filter results in the transfer function \( \frac{s^2}{s^2 + 2\zeta \omega_n s + \omega_n^2} \), effectively a "self-zeroing" integrator. This modifies the open-loop response of the airgap loop by increasing the phase lag at low frequencies to \(-270^\circ\), resulting in conditional stability. The integrator frequency \( \omega_n \) needs to be chosen such that it is substantially lower than the bandwidth of the airgap loop – a typical value might be 1-2 rad/s, resulting in an integrator which is effective to something less than 1 Hz.

Implementation is an interesting issue, because in today's digital world it is natural to consider converting the search coil output signal into digital form and carrying out appropriate processing as a discrete transfer function. However there is a problem because almost inevitably the magnet will be controlled by a PWM amplifier, and the variations in flux density at the amplifier's switching frequency will also be sensed by the search coil. It's straightforward to show that these signals will be substantially larger than those associated with the control action, and will therefore almost inevitably cause aliasing problems associated with control loop sampling at a lower frequency than the PWM frequency. Of course an anti-aliasing filter can be used, but in practice the self-zeroing integrator itself will be very effective for this purpose. The logical conclusion therefore is to implement the transfer function in analogue form, and a typical circuit to achieve this is given by Fig 13.

6. Conclusion

The paper has given an overview of the theoretical and practical issues relating to various forms of magnet control for Maglev vehicles, and in particular has identified the advantages of using an inner flux density feedback loop.

The author's early work on Maglev used current-controlled magnets, much like most other researchers in the field, but the advantages demonstrated by theoretical analysis persuaded him to experiment with flux control, even though it required a certain amount of practical development. Having made the change however, the ease of commissioning and operational robustness reinforced the wisdom of the decision, and the author would not now contemplate developing a new system with anything other than flux control.

References


Fig. 1 Linearised magnet model

Fig. 2 Airgap loop with voltage control

Fig. 3 Nichols chart with voltage control

Fig. 4 Airgap loop with current control

Fig. 5 Nichols chart with current control

Fig. 6 Airgap loop with flux density control

Fig. 7 Nichols chart with flux density control
Fig. 8 Effect of airgap variations (current control)

Fig. 9 Effect of airgap variations (flux control)

Fig. 10 Effect of mass variations (current control)

Fig. 11 Effect of mass variations (flux control)

Fig. 12 Effect of mass variations on step response (1mm change in airgap command)

Fig. 13 Search coil integrator schematic