

Dynamics and control requirements for EMS Maglev suspensions

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Abstract: Any Maglev suspension, whatever the technology, must both support the weight of the vehicle and provide guidance such that the vehicle follows the intended variations in the track position, whilst at the same time providing a suitable level of isolation from the track irregularities. A number of the functions are in conflict, and this paper provides a quantitative overview of the general requirements for suspensions, focussed upon and interpreted for Maglev.

This paper then describes the way in which the control strategy was developed for the Birmingham Airport Maglev vehicle electro-magnetic suspension, which operated successfully in the UK for more than 10 years, in particular to take account of these suspension requirements, the key message being the interactive nature of the dynamics and control issues.

1 Introduction

The developers of Maglev have a tendency to concentrate upon the technology, but the end result must be a system that meets functional and performance requirements that are common to all suspension systems. It is therefore essential that Maglev vehicle designers are not just magnet specialists and/or control engineers, but also that they understand the suspension issues when determining the overall characteristics of their system. This paper firstly gives a summary of these issues and the results of basic analyses to identify the key constraints and tradeoffs, and secondly explains the controller design for the Maglev "people mover" system at Birmingham Airport in the UK, which carried many millions of people during more than ten years of operation from the mid 1980s to the mid 1990s, although its operation is now discontinued [1]. The whole philosophy of its design was to achieve mechanical simplicity, and accordingly its only suspension was the electro-magnetic system provided by its eight controlled d.c electro-magnets. Although some details of the suspension controller have been described previously [2, 3], the full rationale for its development has not been published. This paper describes the design of the vehicle controller, in particular focussing upon the synthesis of the controller structure to meet the range of dynamic requirements that are explained in the first half of the paper.

2 Suspension requirements: general and specific

When the concept of Maglev was first promoted in the 1960s and 1970s it was presumed that its non-contacting nature would intrinsically provide an excellent "riding on air" performance. The reality however proved otherwise, and most Maglev vehicle solutions have used a second stage of suspension involving springs and dampers, even for low and medium speed applications where it is not strictly required.

In particular people initially expected that the larger airgaps afforded by electro-dynamic suspensions (EDS) would result in an easy suspension design, but in practice its lack of damping and inappropriate stiffness also necessitate greater suspension complexity [4], for example as seen in the Japanese Linear Motor Car which has three stages of suspension: the primary electro-magnetic suspension from track to magnets, an intermediate from magnets to bogie frame, and a soft secondary suspension from bogie to body.

It is therefore essential to remember that a magnetically-levitated vehicle must provide more than just “levitation”, because unlike an active magnetic bearing it must provide appropriate suspension characteristics. This section identifies both the general requirements for any suspension system, including the implications for Maglev, before moving on to specific requirements for the Birmingham Airport system.

2.1 General requirements

Any suspension has three functions: to support the load of the vehicle, to guide the vehicle so that it follows the track profile in the vertical and lateral directions, and to isolate the vehicle body and its passengers from vibrations caused by track irregularities. The inputs corresponding to these three requirements are discussed as follows:

2.1.1 Load changes

The suspended load varies principally as a consequence of passengers entering and leaving the vehicle, the magnitude and speed of the variations depending upon the type of system. For a high-speed vehicle these will be relatively small, perhaps 10-15% of the unladen weight, and the changes will occur relatively slowly, e.g. over 60 secs. For a low-speed vehicle the changes may be twice as big in percentage terms, and will occur much faster (c. 10 secs).

2.1.2 Deterministic track inputs

The intended track profile (curves, gradients, and transitions to these features) is designed and laid out by the civil engineer to satisfy comfort requirements. These features will be dependent upon the type of system, with shorter transitions and somewhat higher acceleration levels for lower-speed systems compared with high speed applications. In the vertical direction the transition from level to a gradient will involve a transition giving a superimposed acceleration ranging from 0.5-1.5 m/s², depending upon the type of vehicle (lower acceleration for higher speed systems); the length of the transition depends upon the gradient.

2.1.3 Track irregularities

Deviations of the track from its intended profile can be characterised as a random process with a specified power spectrum. These inputs occur in the vertical, lateral and roll directions with different magnitudes. In the vertical direction the spectrum can be approximately characterised as A_v/f_t^2 m²/cycle m⁻¹, where A_v is the vertical roughness factor and f_t is the spatial frequency in cycle/m, although a refined version has increased attenuation for wavelengths less than around 5m. In the lateral direction the spectrum is often represented as A_L/f_t^3 , where A_L is the lateral track roughness factor.

2.1.4 Suspension constraints

For all the three inputs the design problem is to ensure that none causes the maximum available suspension deflection to be exceeded, in other words it is a constraint in the design process. Generally speaking the softer the suspension the greater will be the deflections caused by all three inputs, although the principal tradeoff arises with respect to achieving a satisfactory ride quality, i.e. the response to the track irregularities. This is a particularly critical issue for Maglev due to the limited airgap (which essentially constrains the maximum suspension deflection). As mentioned earlier, the difficulty has pushed most Maglev solutions towards the use of additional suspension components, which means that the primary (magnetic) suspension can be relatively stiff (and hence easier to design the controller), with the soft secondary suspension providing isolation from the track irregularities.

2.2 Specific requirements for the Birmingham Maglev system

A full description of the vehicle and its requirements is given in [1]. It used four pairs of controlled d.c. electromagnets, one pair at each corner of the vehicle. The magnets and rail were relatively wide (50mm), chosen to give an inherent lateral suspension frequency of around 1.3Hz to give an acceptable ride quality without needing separate guidance magnets. The two magnets at each corner were laterally offset: they were primarily controlled together for vertical suspension control, but some differential action was introduced to provide lateral damping.

The load-carrying requirements were for a tare (unladen) vehicle of 5 tonnes, rising to 8 tonnes when fully laden, with an operating speed of 50km/h (13.8 m/s). Although the particular track profile used at Birmingham Airport did not have any particularly large deterministic inputs in the vertical direction, the vehicle was designed to a specification based upon city centre operation with frequent changes from ground to first floor levels, for which a 10% gradient with 1.5 second transitions was required. For the track quality an alignment corresponding to secondary quality railway track was used in order to minimise the track cost, and a corresponding vehicle acceleration in the vertical direction of 3.5% g rms was specified to meet ride comfort requirements for a low speed vehicle with rather short journey durations (around 90 seconds for the airport application). Electromagnet design was based upon a normal operating airgap of 15mm, implying a maximum r.m.s suspension deflection of 5mm, i.e. one third of the maximum to give a low probability of contact between the magnets and the track.

It is possible analytically to define the limitation in the tradeoff between ride quality and suspension deflection [5]. Using the track irregularity spectrum described in Section 2.13 and based upon transfer function representation of suspension performance expressions for the r.m.s. values for the acceleration and deflection suspension can be shown to be

$$\begin{aligned}\ddot{z}_{\text{rms}} &= 40 \sqrt{A_v V} f_o^{1.5} \\ g_{\text{rms}} &= 1.8 \sqrt{A_v V} f_o^{-0.5}\end{aligned}$$

where $A_v = 10^{-6}$ is the track roughness factor for secondary quality track, $V = 13.8\text{m/s}$ is the vehicle speed. f_o is the cut-off frequency for a second-order suspension characteristic, and a value of 1.8Hz gives suitable values for both requirements. With a higher quality track, for example having a roughness factor of 2.5×10^{-6} , a speed four times higher is in principle possible, although associated with higher speed operation will usually be increased ride quality requirement and so the practical speed limit for a single-stage electro-magnetic suspension is about 2-3 times higher, i.e. speeds up to around 150km/h.

In the lateral direction there was a requirement to negotiate curves with a minimum radius of 20m, although because these are negotiated at low speed it becomes a problem of geometry rather than dynamics. The vehicle configuration, which as described above used the inherent lateral stiffness provided by the suspension magnets rather than having separate guidance magnets, provided about $\pm 30\text{mm}$ of lateral suspension movement and so the lateral suspension dynamics are significantly less critical, and not therefore included in this paper.

3 Magnet control

The basic issues involved in control of an electro-magnetic suspension are well understood. The force produced by the magnet is a non-linear function of the magnet current and the airgap, in the latter case an inverse relationship which creates a fundamentally unstable open-loop characteristic [6]. This can either be visualised as a (non-linear) negative spring, or the suspension's linearised transfer function characteristic can be shown to have the general form $K/(-s^2 + as^3)$ which has a positive real pole (eigenvalue). A linearised representation of the dynamics of a single-magnet suspension is shown in Fig 1, where V, I, B, F and G are (respectively) the voltage, current, force and airgap; suffix zero

indicates the nominal values of these variables, and the lower case letters indicate small variation about these nominal values, e.g. $I = I_0 + I$; K_i , K_b and K_g are linearised parameters derived from the non-linear electro-magnetic equations. Please see [6] for more details if required, but this is a well-known representation.

Stability is achieved by rapidly increasing/decreasing the excitation to compensate for increasing/decreasing airgap. There is a minimum value of feedback gain from airgap measurement to magnet excitation which is needed to overcome the basic instability of an uncontrolled electro-magnet, and this needs to be combined with phase advance compensation to provide good damping. Also, most researchers have recognised that controlling the magnet voltage is not satisfactory because of the additional phase lag introduced by the magnet leakage inductance (represented by the s^3 term in the transfer function).

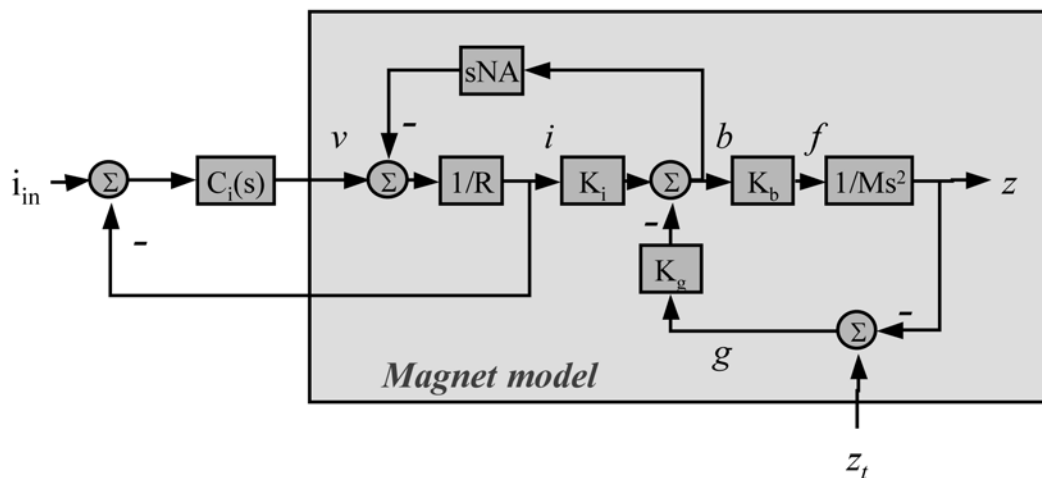


Fig 1: Linearised magnet representation (including current control loop)

3.1 Current control of magnets

The use of fast-acting current control (see Fig 1), which is often provided within modern electronic power amplifiers, is a natural option to overcome the inductive effects mentioned in the previous paragraph. However, although it is not widely recognised, careful analysis shows that current-controlled magnets are fundamentally limited in their controllability [7]. The minimum gain required to provide stability, also mentioned in the previous paragraph, essentially forces a certain bandwidth for the suspension. This depends upon the airgap, and is typically 5-10 Hz for an airgap in the 10-15 mm range: not only is this much higher than is required to achieve a suitable ride quality, but also in practice there will usually be problems due to the excitation of flexible vibration modes in the vehicle structure.

3.2 Flux control of magnets

The alternative is to use fast-acting feedback control of the airgap flux density – see Fig 2. Since force is directly dependent upon flux density, irrespective of the airgap, this feedback overcomes the fundamental instability of the magnetic circuit without requiring airgap feedback, converting the suspension transfer function to K/s^2 . This can be seen from Fig 2 because the destabilising effect of the airgap appears within the flux loop, and as long as the control effect is fast enough it will be neutralised. Airgap feedback is still needed, again with a phase advance to provide damping, but the minimum gain requirement no longer applies and there is now much greater freedom to choose a suitable bandwidth for the airgap feedback loop.

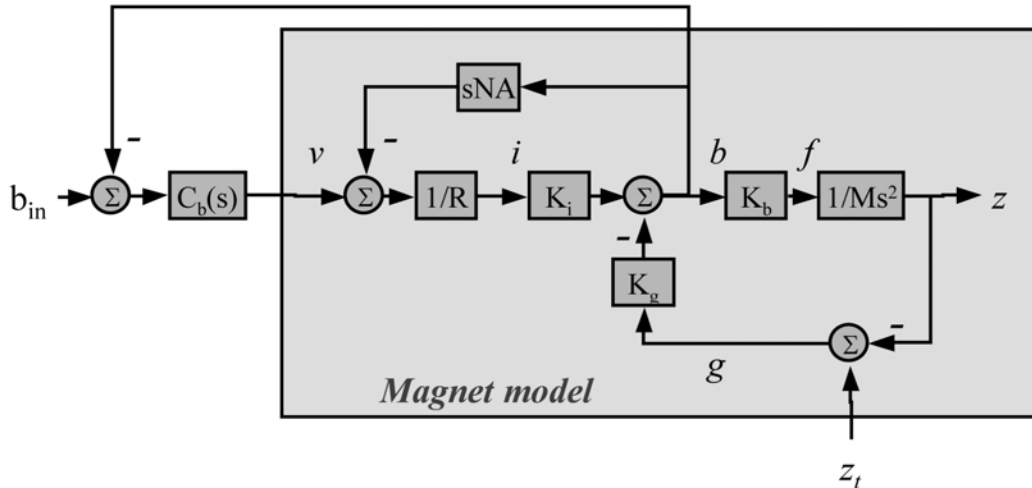


Fig 2: Flux-controlled magnet

The flux loop controller is relatively straightforward to design, because the open-loop transfer function from voltage v to flux density b is approximately $1/sNA$ at high frequencies. To give a bandwidth f_b the flux loop gain needs to be $G_b = 2\pi f_b NA$ V/T, and experience has shown that it is perfectly feasible to design for 50Hz, i.e. significantly higher than the dominant suspension frequencies. It also makes sense to add an integral term to further improve the performance at lower frequencies; detailed design can be done using root locus or frequency domain techniques (Bode, Nichols, etc.) but typically this will be applied with a break frequency of around 20Hz giving an integrator time constant of $\tau_b = 1/40\pi$ s, and resulting in a flux compensator

$$C_b(s) = G_b (1 + s\tau_b)/s\tau_b$$

It is of course necessary to provide a measurement of flux density, which is not as straightforward as current. The key issues are discussed in [7]. For the Birmingham Airport Maglev vehicle search coils embedded in the polefaces of the magnets were used. The signals have to be integrated to get flux density, and a self-zeroing response is needed in practice:

$$H_b(s) = \frac{s/\omega_b^2}{1 + 1.4(s/\omega_b) + (s^2/\omega_b^2)}$$

4 Single magnet suspension controller

4.1 Airgap control

Having achieved robust control of each magnet using flux feedback, the next step is to develop the suspension controller for a single magnet. The obvious solution, shown in Fig 3, is to provide an airgap feedback gain G_g to give an appropriate suspension frequency, i.e. in the 1.5-2Hz range as discussed in section 2.2.

Its effect can be thought of as providing a spring with a value $2G_g F_o/B_o$ (N/m). The well-known expression for the natural frequency $f_n = \sqrt{(K/M)}/2\pi$ can then be used. Since $F_o = Mg$, where g is the acceleration due to gravity, the natural frequency is $\sqrt{(2G_g g/B_o)}/2\pi$ and it becomes straightforward to calculate the value of control gain G_g to give the required frequency. However, at this stage it's necessary to consider the effect of load changes. If δ is the static deflection under the vehicle weight, the natural frequency can also be expressed as $\sqrt{(g/\delta)}/2\pi$, and a simple calculation will show that the static deflections are approximately 100mm for a 1.6Hz suspension frequency, 250mm for 1Hz, etc. Although in practice the load change will only be a small proportion of the static weight, it is clear that the stiffness required to keep the effects of such changes to within perhaps 5mm is not consistent with the requirements for ride quality.

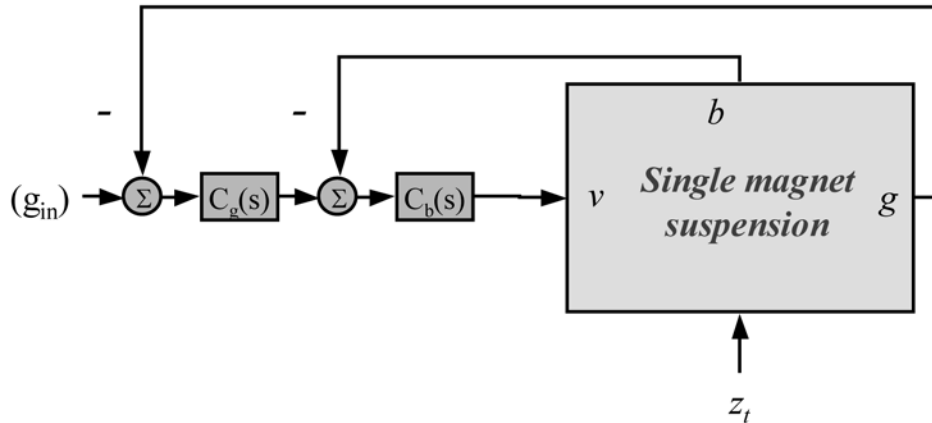


Fig 3: Basic airgap feedback suspension controller (including flux control)

4.2 Complementary filter control

An effective solution arises from observing that controlling the magnet can theoretically be done by feeding back the absolute position of the suspended load z instead of the airgap, and this leads to the idea of a dual feedback approach utilising the airgap at low frequencies (to provide guidance) and the absolute position at high frequencies (to provide isolation) – see Fig 4. A simple analysis shows that, if the low-pass and high-pass filters that are used to provide the guidance and isolation functions (respectively) add to unity (i.e. they are algebraically complementary), then the stability of the composite loop (tuned using $C_g(s)$) is not dependent upon the filter transfer functions; further it can be shown that the basic suspension transfer function z/z_t is closely given by the low-pass filter transfer function $LP(s)$ and the airgap response g/z_t is given by $HP(s)$. Note that the main loop compensator needs to include phase advance compensation, giving the transfer function

$$C_g(s) = G_g (1 + sk\tau_g)/(1 + s\tau_g)$$

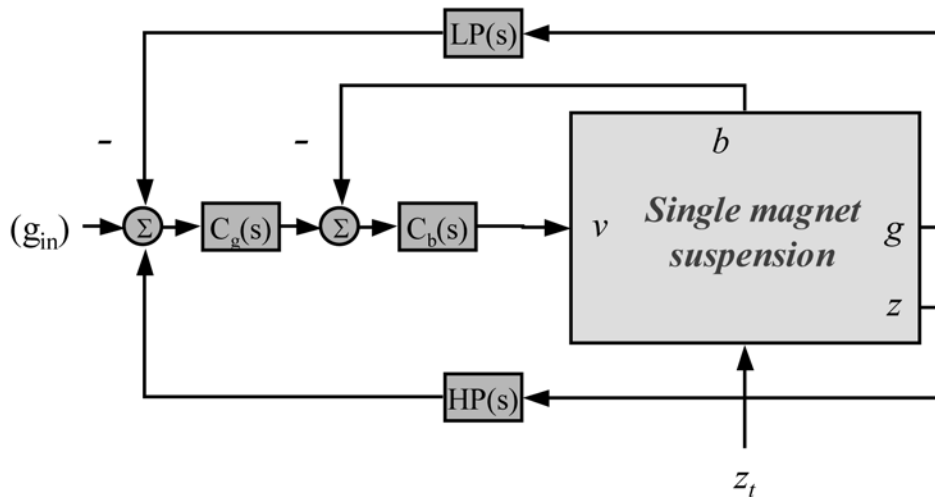


Fig.4 Complementary filter suspension controller

The result is a robust control structure in which the various functions are separated: stability is provided by the inner flux feedback loop, tuned using $C_b(s)$; response to load changes (and other force disturbance inputs) is reacted by the relatively fast-acting displacement loop, tuned using $C_g(s)$ independently of the settings of the suspension filters $LP(s)$ and $HP(s)$ to give a frequency of about 5Hz (plus an appropriate phase advance compensator); response to track inputs is determined by the

suspension filters, with the choice of $C_g(s)$ and $C_b(s)$ having only minor effects upon the fundamental suspension response.

The complementary filter technique requires a measurement (or estimate) of the absolute vertical position of the suspended load. However this is only required at higher frequencies (typically 1Hz and higher), and so it is possible to obtain a signal by double-integrating the output from an accelerometer. In order to cope with slow offset variations from the accelerometer it's also necessary to have a self-zeroing action, leading to a third order transfer function as follows:

$$H_i(s) = \frac{s / \omega_i^3}{1 + 2(s / \omega_i) + 2(s^2 / \omega_i^2) + (s^3 / \omega_i^3)}$$

The overall controller has now become dynamically complex, but the parameters are not highly dependent upon the magnet characteristics (which distinguishes the approach from “modern” model-based design techniques) and it has proved to be very robust, coping well with significant airgap variations and load changes in operation within the need for adaptation of the control parameters.

5 Whole vehicle controller

The final stage of controller development is to take the concept derived in the previous section and extend it for the control of the four magnet pairs. Independent control of each magnet pair, i.e. copying the controller derived in the previous section four times, has a number of limitations and problems, in particular that all the loops are intrinsically coupled via the vehicle body. Accordingly a “modal controller” was developed in which the measurements from the four corners are converted into vertical, pitch and roll motions and then processed independently in a separate controller based upon the complementary filter technique for each mode, as shown by Fig 5. These are then used to provide appropriate flux command signals for each magnet with its inner flux control loop. In a completely symmetrical vehicle the three loops would be uncoupled, although in practice there will be some interactions; however the fundamentally robust nature of the strategy easily accommodates these interactions.

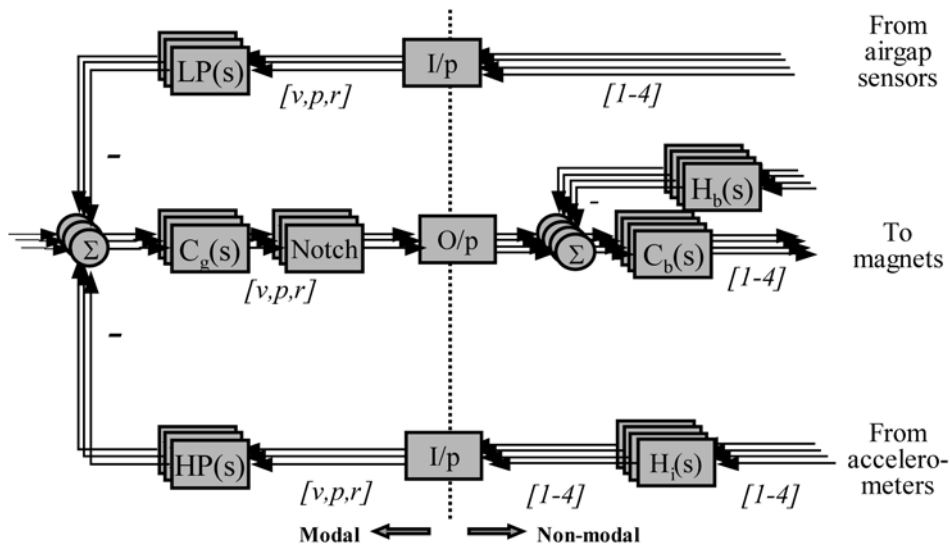


Fig.5 Vehicle controller – modal form

This modal control is achieved by converting the absolute position and airgap signals at each magnet into vertical, pitch and roll signals; the input matrix (I/p) for the airgap signals is shown below

$$\begin{bmatrix} g_v \\ g_p \\ g_r \end{bmatrix} = \begin{bmatrix} 0.25 & 0.25 & 0.25 & 0.25 \\ 0.25 & -0.25 & -0.25 & 0.25 \\ 0.25 & 0.25 & -0.25 & -0.25 \end{bmatrix} \begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \end{bmatrix}$$

Corners are numbered 1-4 clockwise, with 1 at the front right corner, so 1 and 2 are at the front and rear of the vehicle respectively.

(N.B. it would also be possible to process the acceleration signals in modal form, but it was found better to combine the accelerometer and double integrator processing electronics in a single sensor unit that can be tested and calibrated off the vehicle prior to integration into the vehicle suspension control system.)

The controller generates flux commands for each mode, which are then converted back into independent flux commands for each magnet by means of the output matrix (O/p):

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 1 \\ 1 & -1 & -1 \\ 1 & 1 & -1 \end{bmatrix} \begin{bmatrix} b_v \\ b_p \\ b_R \end{bmatrix}$$

The scheme provides additional features. Firstly it is possible to have different cut-off frequencies in the pairs of complementary ride control filters, which is advantageous for ride quality with the pitch and roll filters at a lower frequency than in the vertical mode. Secondly, structural flexibilities are generally excited in a modal sense, and so a single notch filter can be included in each of the modal paths (whereas all the filters would need to be included in each of four controllers with the non-modal form).

The overall result is a controller with a complexity as given in the table below. Note that only one suspension filter is given – this arises from the complementary nature of the filter pair, which means that a single filter can readily be used.

Table 1 Controller components and complexity

Description	Complexity	Number	Total
Flux loop controller	1 st order	4	4
Flux loop sensor processing	2 nd order	4	8
Main loop controllers	1 st order	3	3
Main loop notch filter	2 nd order	3	6
Suspension filters	2 nd (or 3 rd order)	3	6 (or 9)
Accelerometer processing	3 rd order	4	12
Total:			39 (or 42)

It can be seen that, although the overall controller is complex, its complexity is a consequence of the structure because individual elements are simple. In addition, commissioning is a straightforward process because of the separation of the functionality: for example each modal loop's gain, phase advance and notch filter characteristics can be optimised independently of each other, and then their dynamic performances in response to track input changed by means of a suitable choice of the complementary suspension filters.

6 Conclusions

The Maglev controller has been derived through a “structured classical” control design approach, based strongly upon a fundamental understanding of the physical system and its requirements. It is interesting to contrast this with modern optimal and robust design methods in which the knowledge of the system is embedded within the model that the designer provides and is used mathematically to produce the controller.

The overall design approach is applicable for any form of active suspension concept. This is illustrated by the fact that it was successfully applied for an active lateral suspension on a railway vehicle [8]. Instead of magnets two force-controlled servo-hydraulic actuators were used, and two suspension modes (lateral and yaw of the vehicle body) were controlled instead of the three vertical modes (see Fig 6). However the basic control structure and design philosophy were in other respects identical.

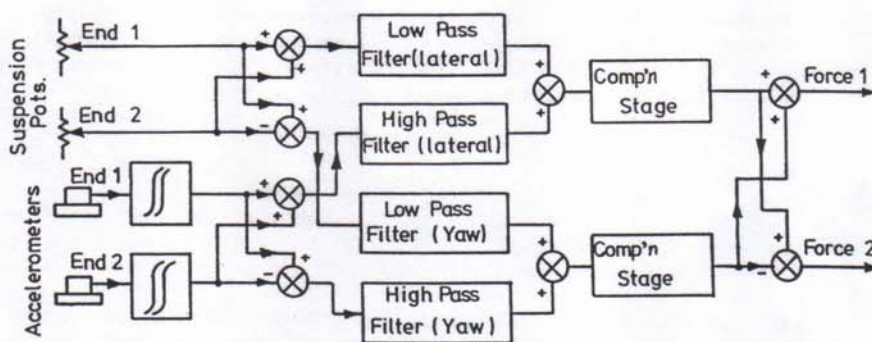


Fig 6: Controller for active lateral railway suspension

The main conclusion of this paper is the emphasis upon understanding fully the suspension requirements and creating a Maglev suspension controller which properly satisfies the multiple design objectives.

7 References

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