Levitation in Control

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Abstract

At UWS, the School of Engineering offers the post graduate Masters degree and students can complete the Advanced Control Systems unit as part of their units. As part of the practical work in ACS the students must complete set practicals and a project that deals with a levitation apparatus. Specifically the students start with an electromagnet, led light source and LDR and are required to develop an apparatus that can levitate a ferrous object. The students are directed to a specific publication as a sample of the methodology to use; a linearized model and controller have to be developed over the 14 teaching weeks. Students are given swipe card access to a laboratory area. Test equipment is issued as required for use in parameter identification. Meeting with a tutor occurred in special tutorials for one hour each week in which students could discuss specific aspects and directions as they progressed their designs. At the end of the Autumn Session students were required to take part in a forum and to present their results, whether successful or not, and as well submit a detailed report of their efforts. Students worked in groups of no more than four and 14 students were involved in total. While a several groups came close to achieving the desired end objective, no group was able to successfully levitate a ferrous object. One group was successful but employed a non-linear method rather than a linearized model. The major problem identified by some of the groups was the design of the electromagnet coil while other groups identified problems with the light source and sensor as the limiting factor. Investigations by the unit co-ordinator identified a major problem with the design of the coil. Using a redesigned coil with current control levitation was achieved. The next iteration of the project should see successful end results.

1. Introduction

The University of Western Sydney attracted some 3052 postgraduate Masters by Coursework students in 2010. This compares with 1860 such students in 2005 [1]. The School of Engineering at UWS offers Masters degrees by coursework and the Advanced Control Systems (ACS) is one of the units that can be taken up as part of the coursework. In 2010 the students in ACS undertook a session long project that involved magnetic levitation. Fourteen students took up the challenge in 2010 and eleven in 2011.

The levitation project's design oriented remit entailed suspending an object under an electromagnet, the starting point being the electromagnet itself. The project is a practical real world problem. The problem is open ended in that no two electromagnets assemblies are identical. Designs used by the students must be particular to their apparatus. Knowledge gained can be integrated and applied to a real world problem.

The adoption of magnetic levitation demonstrations as a tool of control education is not new [3], [4], [5], [6]. The adoption of the levitation project would allow the postgraduates to become fully engaged with a non-trivial real world problem and allow them to further develop their own abilities as professional engineers. Engineers Australia for example sets certain attributes that graduates should acquire, such as in depth technical competence and the ability to identify the problem at hand and forming and creating a solution.

2. System Description

The control objective set was to hold in mid air vertical suspension an object by means of a magnetic attractive force against the pull of gravity. In the first iteration of the project, the object was a steel ball approximately 13 mm in diameter. The type of magnetic levitation used was an attractive type, as distinct from a repulsion type [2]. In the second iteration, a table tennis ball was used with a small but strong magnet inserted inside. This object would make use of the repulsion provided by the permanent magnet along with the attraction of the electromagnet, resulting in a larger gap, giving a more visually appealing end result.

The students are supplied with a wound electromagnet hanging vertically from an inverted U-shaped frame, approximately 30 cm wide and 30 cm high, suitable for table top use. The general arrangement is shown in Figure 1. The students are supplied with an LED light source and data sheet and a light sensitive sensor consisting of a light dependent resistor (LDR). The sensor components have to then be mounted, by the students, on the legs of the apparatus. There are pedagogical advantages to having the students involved with, and engaged in, the construction of the apparatus.

The students are given swipe card access to a project room in which they can set up their apparatus and perform testing. Test equipment is provided by way of power supplies, signal generators, oscilloscopes, multimeters, experimental boards and tool-kits. Lockers are also provided so that equipment does not need to be carried around but can be stored away as needed. Simulations are encouraged and can be completed in separate computer laboratories.

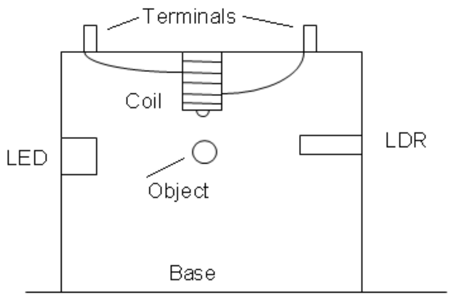

Figure 1: Physical arrangement of apparatus

3. Getting Started

The starting point for the postgraduates is the paper by Green, Hirsch and Craig [3]. This sets up the basic system modeling that will be needed in the process. The nonlinear nature of the problem becomes apparent as the student work through the modeling needed to get started. A mathematical model is the first item to complete, starting with the object itself.

As shown in Figure 2, with x the distance from the face of the electromagnet, the behaviour of the object will be given by:

$$m\frac{dx}{dt} = mg - f(x,i) \tag{1}$$

where *m* is the mass of the object, *g* the acceleration due ti gravity and *f(x, i)* represents the magnetic force of attraction. As developed in [3] the magnetic force is given by

$f(x,i) = C\left(\frac{i}{x}\right)^2$, where $C = \frac{L_0 x_0}{2}$ is called the force constant. L_0 is the inductance contribution due to the object and x_0 is the desired equilibrium distance at which the object will suspend. In practice *C* is determined experimentally. Substituting for *f(x, i)* in (1) gives

$$m\ddot{x} = mg - C\left(\frac{i}{x}\right)^2 \tag{2}$$

At equilibrium since $\ddot{x} = 0$ the value of *C* may be computed from $C = mg\left(\frac{x_0}{i_0}\right)^2$ where i_0 corresponds to the current needed to achieve a displacement of x_0.

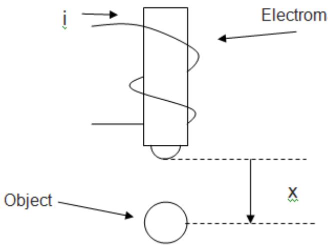

Figure 2: Model parameters

A linearized model about the equilibrium point defined by x_0 and i_0 gives

$$f = C\left(\frac{i_0}{x_0}\right)^2 + \left(\frac{2Ci_0}{x_0^2}\right)\delta i(t) - \left(\frac{2Ci_0^2}{x_0^3}\right)\delta x(t) \tag{3}$$

Allowing for the weight *mg* to be matched by $C\left(\frac{i_0}{x_0}\right)^2$ leads to the transformed equation via (2) and (3):

$$\frac{X(s)}{I(s)} = \frac{-\left(\frac{2Ci0}{x_0^2}\right)}{s^2 - \left(\frac{2Ci_0^2}{mx_0^3}\right)} \tag{4}$$

From (4) it is apparent that there is one open loop pole in the left half of the s-plane, since from (4) the open loop poles are

$$s_{1,2} = \pm\sqrt{\frac{2Ci_0^2}{mx_0^3}}\,. \tag{5}$$

The model equations allow a block diagram to be developed, as shown in Figure 3.

The block diagram can be further developed by incorporating the electromagnet coil. Treating the coil as a lumped parameter model:

$$v(t) = ri(t) + L\frac{di}{dt} \tag{6}$$

Taking the usual approach, the transfer function is a first order lag given by

$$\frac{I(s)}{V(s)} = \frac{1}{sL + R} \tag{7}$$

There is an alternative to how the electromagnet coil is modelled. By making use of a voltage to current converter, the current in the coil may be controlled in proportion to the applied voltage. In this case the transfer function for the *RL* block in Figure 3 becomes a simple gain. This is the approach taken during the second iteration of the project.

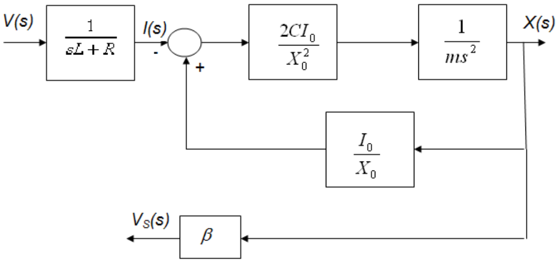

Figure 3: s-domain model

The activities required to complete the project were generally divided into four stages, namely determination of the equilibrium point distance X_0 and current I_0; measurement of the coil inductance and resistance; identifying the sensor gain β; and designing the phase lead module.

3. Limited success

Having constructed their apparatus and identified parameters, the students would apply root locus techniques to design a compensator with suitable gain. At this stage problems began to appear with the magnet. In the many published papers the configuration of open loop poles was such that the poles associated with coil, $s = -L/R$, were typically located in the s-plane to the left of the left half plane part of the double poles given in (5). The coils the students worked with had this pole located to the right, restricting design possibilities. The end result was that sustained suspension was not achieved by use of a linearization method. However, some students adopted a non-linear controller and did achieve suspension [6].

The problems and how they were dealt with by the students were discussed openly in an end of session seminar at which the students presented their results and conclusions. The properties of the electromagnet's coil was a major difficulty. This had not been the intention when the electromagnet coils were manufactured. The basic problem was the combination of the resulting inductance values and the small resistance presented by the coil. Typically the inductance was measured at 135 mH and the resistance, as measured by an ohmmeter, 6.5 Ω, so the pole associated with the coil inductance and resistance was at -48 rad/s. This compared to the double poles of (5) at ±41 rad/s. New coils had to be manufactured for the next iteration, planned for the following year, 2011.

Investigations in the post teaching period identified the problem with the electromagnet was exacerbated by the lack of repeatability in the output of the sensor. In the original magnet design, metal washers had been used so the end of the magnet provided a large magnetic area to which a ferromagnetic object could be attracted. This lead to a loss repeatability in the sensor output. The solution was to rewind the coils with a small, coned shaped end and to use only non-magnetic washers. Further changes entailed the use of a table tennis ball with a strong permanent magnet glued to the inside. This was found to enhance the visual effect and resulted in larger gap. The type of electronic modules was also altered, with the control of the current through the coil, as mentioned, obviating the need to include the first order lag associated with the RL circuit formed by the coil. This arrangement was proven and suspension was achieved, as shown in Figure 4.

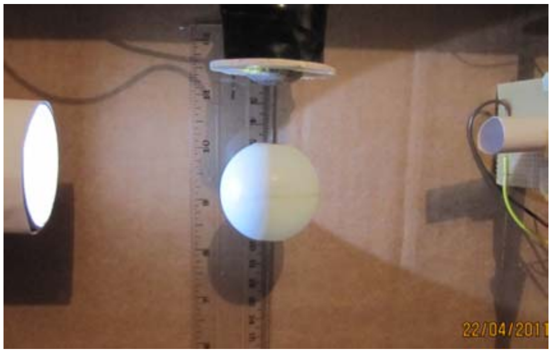

Figure 4: The ball in suspension

4. Around the Equilibrium

As part of the second iteration, the use of the current controller simplified the problem to some extent. The concept that had to be fully appreciated was the operation around the operating point. The Taylor series expansion allowed ready linearization, but the physical interpretation had to be fully understood. At this stage the students were directed to another publication which helped in gaining a physical understanding of the equilibrium [7].

The electronic modules used realized the arrangement shown in Figure 5. The heart of the final stage of the project was the compensator module, in this case an active phase lead circuit. By setting up the correct voltage from the sensor and the correct current in the electromagnet coil, it was only necessary to make allowances for variations as the object moved roughly at the chosen point of suspension.

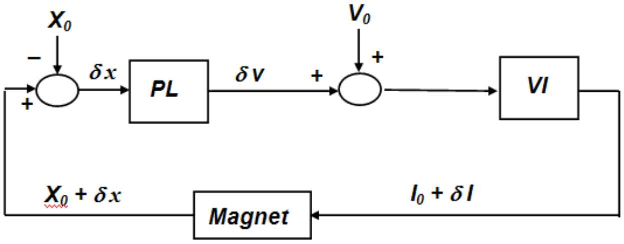

Figure 5: Variations around equilibrium

5. Conclusion

The postgraduate students took on the challenge of designing, implementing and testing a magnetic levitation project. Guided by successful approaches in published papers, problems with the apparatus were identified as the project ran its course. A major problem was in the design of the electromagnet's coil. Attempts at compensating for the unsuitable coil designs were many and varied. At first some students attributed the problems to the sensor, and some to the sensor and coil combination. The end of session seminar included lively discussions of the pros and cons. Most students agreed the task became difficult as a result of unintended additional constraints. Most agreed the experience was a "useful teaching aid" in the area of control systems. In the second iteration, new coils have been manufactured and a slightly modified approach should see greater success at achieving sustained suspension.

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