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Modelling of vertical control in magnetic levitation for building isolation during earthquakes

E. Crozier
Dept of Mechanical Engineering, École Nationale d'Ingénieurs de Saint-Étienne, Saint-Étienne, France.

C. Zhou, J.G. Chase & G.W. Rodgers
Department of Mechanical Engineering, University of Canterbury, Christchurch.

ABSTRACT

Earthquakes cause significant damage to buildings due to strong vibration of the ground. Levitating houses using magnets and electromagnets would provide a complete isolation of ground motion for protecting buildings from seismic damage. Two types of initial configuration for the electromagnet system were proposed with the same air gap (10mm) between the electromagnet and reluctance plate. Both active and passive controller are modelled to investigate the feasibility of using a vibration control system for stabilizing the magnetic system within the designed air gap (10mm) in the vertical direction. A nonlinear model for the magnetic system is derived to implement numerical simulation of structural response under the earthquake record in Christchurch Botanic Gardens on 21 February 2011. The performance of the uncontrolled and the controlled systems are compared and the optimal combination of control gains are determined for the PID active controller.

Simulation results show both active PID controller with constant and nonlinear attracting force are able to provide an effective displacement control within the required air gap (+/-5mm). The maximum control force demand for the PID controller in the presence of nonlinear attracting force is 4.1kN, while the attracting force in equilibrium position is 10kN provided by the electromagnet. These results show the feasibility of levitating a house using the current electromagnet and PID controller. Finally, initial results of passive control using two permanent magnets or dampers show the structural responses can be effectively reduced and centralized to +/-1mm using a nonlinear centring barrier function.

1 INTRODUCTION

Earthquakes cause significant damage, and in Christchurch, $16B of damage to homes alone. A range of technologies have been developed to minimise the response energy of buildings in earthquakes, including seismic dampers (Rodgers et al., 2008, Hazaveh et al., 2018a), structural reinforemenets (Dashti et al., 2017, Golondrino et al., 2019) and base isoloation systems (Kelly, 1986). The isolation of structures from the ground motion is an effective way to protect the structure from damage in a strong earthquake. The basic concept of base isolation is to provide a low lateral stiffness between the structure and the foundation to lengthen the natural period of the building from its fixed-base value and the dominant periods of the seismic ground motion. Thus, the transmission of earthquake motion and force to the superstructure of the isolated building can be significantly reduced. However, base isolators cannot ensure a complete isolation of damage and may not be operational as the changes of soil conditions, environmental effects and earthquake inputs (Jangid and Datta, 1995, Zhou et al., 2015).

Electromagnets can create a magnetic field to counteract the gravity forces, thus would potentially provide a complete lift of houses from the ground motion to avoid seismic damage. Magentic levitation using electromagnets have been used instrustry machine bearings and fast-train rail systems. This paper focuses on a preliminary anlaysis of design and vertical control for house levitation using electromagnets-iron plate systems. Dynamic analysis and modelling of two initial configurations are conducted with and without the PID controller.

2 MODELLING FOR MAGNETIC LEVITATION

2.1 Electromagnet Configurations

Two configurations were proposed by Strahan (Strahan, 2019) as shown in Figures 1-2. The structural column is designed to go through the reluctance plate in Configuration A, Configuration B provides three beams to connect with the central column on top of the reluctance plate.

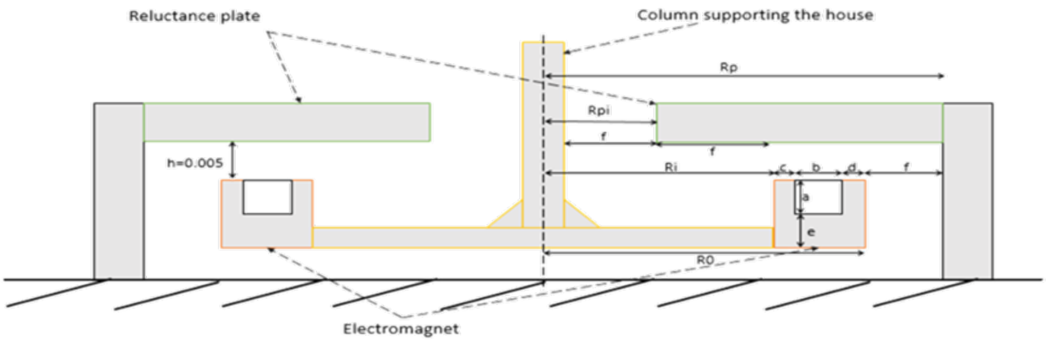


Figure 1: Configuration A for electromagnet reluctance plate.

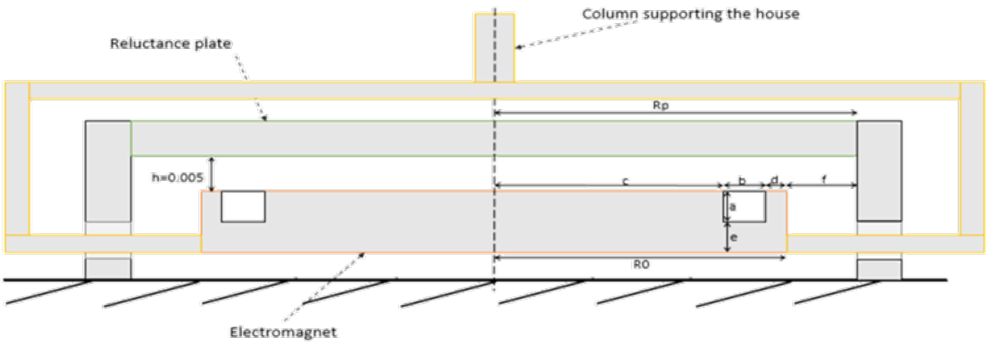


Figure 2: Configuration B for electromagnet reluctance plate.

2.2 Control-free Modelling

The dynamic equation of motion in vertical direction is defined:.

$$\begin{cases} m\ddot{V}_g - mg + f_{attr}(1\,/\,h^2, i) = 0 \\ \qquad h(t) = \iint \ddot{V}_g(t) \end{cases} \tag{1}$$

where m is the mass of the building, g is the gravity, $\ddot{V}_g$ is the ground acceleration and $f_{attr}$is the nonlinear attraction force determined by gap between the reluctance plate and the electromagnet plate, as shown in Figure 3. Thus, the equilibrium position is defined at h=0, and the oscillation limit for the electromagnet is -5mm to 5mm. The attraction force is increasing as h changes from negative to positive.

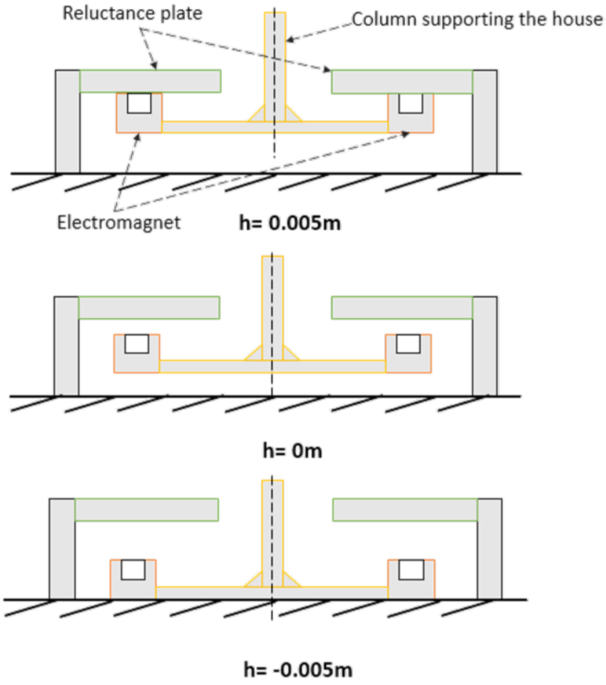


Figure 3: Defined electromagnet position h.

2.3 PID Control Modelling

A PID controller is assumed to be added in Equation (1) for active control, which yields:

$$m\ddot{h} + k_p h + k_d \dot{h} + f_{attr} = m(g - \ddot{V}_g) \tag{2}$$

where k_p and k_d are propotional and derivative control gains, respectively. the changes of k_p and k_d determines the change of rise time, steady-state error, settling time and overshoort. The second order differential Equation (2) can be transformed to the first order state space equation:

$$\dot{X} = \begin{bmatrix} \dot{h} \\ \ddot{h} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \frac{-k_p}{m} & \frac{-k_d}{m} \end{bmatrix} X + \begin{bmatrix} 0 \\ 1 \end{bmatrix} F_n \tag{3}$$

$$F_n = (g - \ddot{V}_g) - \frac{f_{attr}}{m} \tag{4}$$

where X is the state vector and can be solved via numerical integration. The attraction force can be updated at each time step and iteration.

2.4 Passive Control Modelling

A passive control is also modelled with the use of permanet magnets or dampers, as shown in Figure 4. The interest of a passive control compare to an active control is it requires no additional external intervention and external energy supply. Thus, the dynamic equation for passive control system can be written:

$$m\ddot{h} + (f(h) + f_{attr})\dot{h} = m(g - \ddot{V}_g) \tag{5}$$

where *f*(*h*) is the barrier function for centring the control loop, can be defined (Chase et al., 1999):

$$f(h) = \alpha e^{n\left(\frac{|h|}{h0-|h|}\right)} - 1 \tag{6}$$

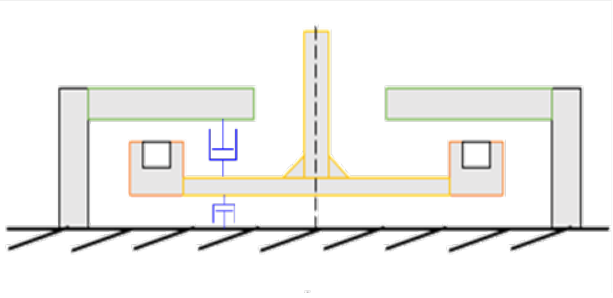


Figure 4: Passive control with two dampers.

3 RESULTS AND DISCUSSION

The performance of the levitation control is tested against the earthquake record for Christchurch Botanic Gardens on 21 February 2011. Each electromagnet plate is assumed to support a 10 tones mass. Table 1 shows the the demand control force under a range of combination of k_p and k_d. The minimum control force is 4.1kN with k_p=1000kN/m and k_d=25kNs/m. The vertical displacement for the levitated house with the designed active control are significantly reduced within the gap limit (-5mm,5mm), as shown in Figure 5. In addition, the control force is much smaller than the resluted attraction force, as shown in Figure 6. This results indicates the tension or current for the calculated control force is less demanding than the power for lifting the house. Therefore, the vertical control for house levitation during a sinigficant earthquake input would be feasible given the required power for magnetive levitation is satisfied.

Table 1: Changes of control force (N) over kp and ke.

$k_p \backslash k_d$	22000	24000	25000	26000	27000	30000	35000	50000
0	9.9E+04	5.5E+03	5.3E+03	5.4E+03	5.4E+03	5.7E+03	6.2E+03	8.0E+03
100	9.9E+04	5.5E+03	5.3E+03	5.4E+03	5.4E+03	5.7E+03	6.2E+03	8.0E+03
1000	1.0E+05	5.5E+03	5.3E+03	5.4E+03	5.4E+03	5.7E+03	6.2E+03	8.0E+03
10000	1.1E+05	5.5E+03	5.3E+03	5.4E+03	5.4E+03	5.6E+03	6.2E+03	8.0E+03
100000	4.0E+05	5.2E+03	6.3E+05	5.3E+03	5.3E+03	5.5E+03	6.1E+03	7.9E+03
1000000	1.3E+08	4.2E+03	4.1E+03	4.1E+03	4.2E+03	4.8E+03	5.8E+03	7.8E+03
10000000	5.7E+09	3.6E+08	2.1E+04	2.0E+04	1.9E+04	1.7E+04	1.4E+04	1.2E+04
100000000	1.2E+05	1.0E+05	9.5E+04	8.9E+04	8.5E+04	7.8E+04	7.0E+04	5.3E+04

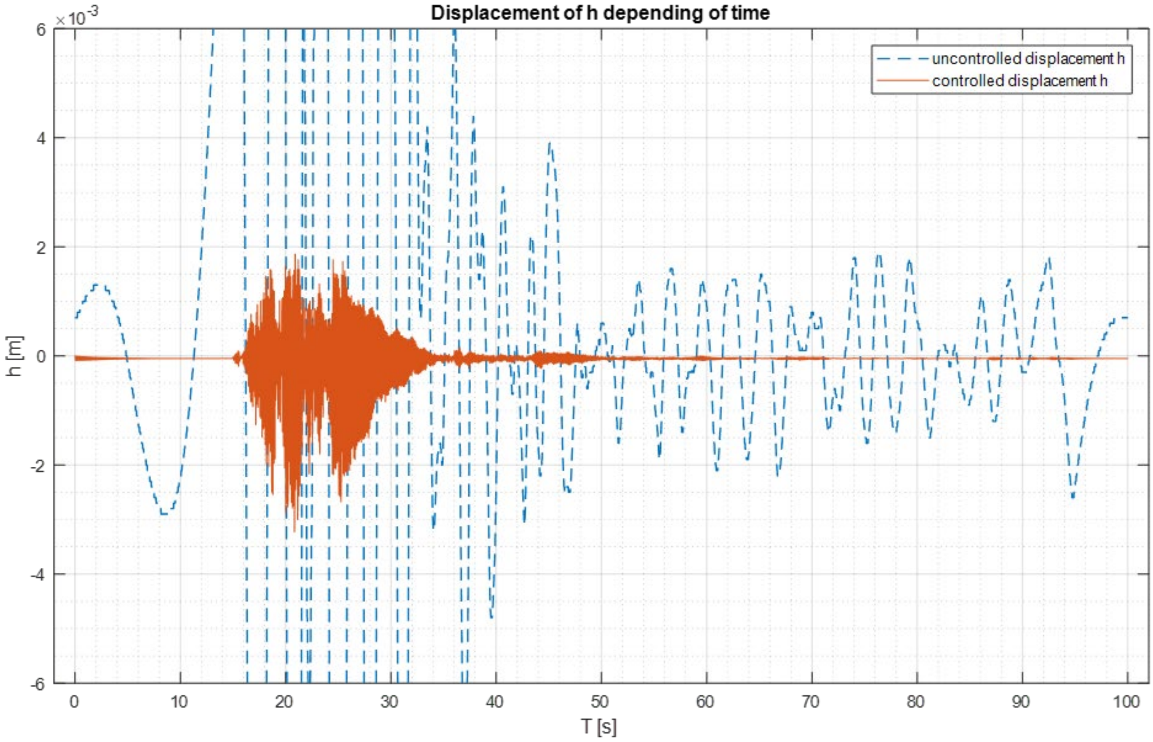


Figure 5: Comparing the vertical displacement between the uncontrolled and active-control simulation.

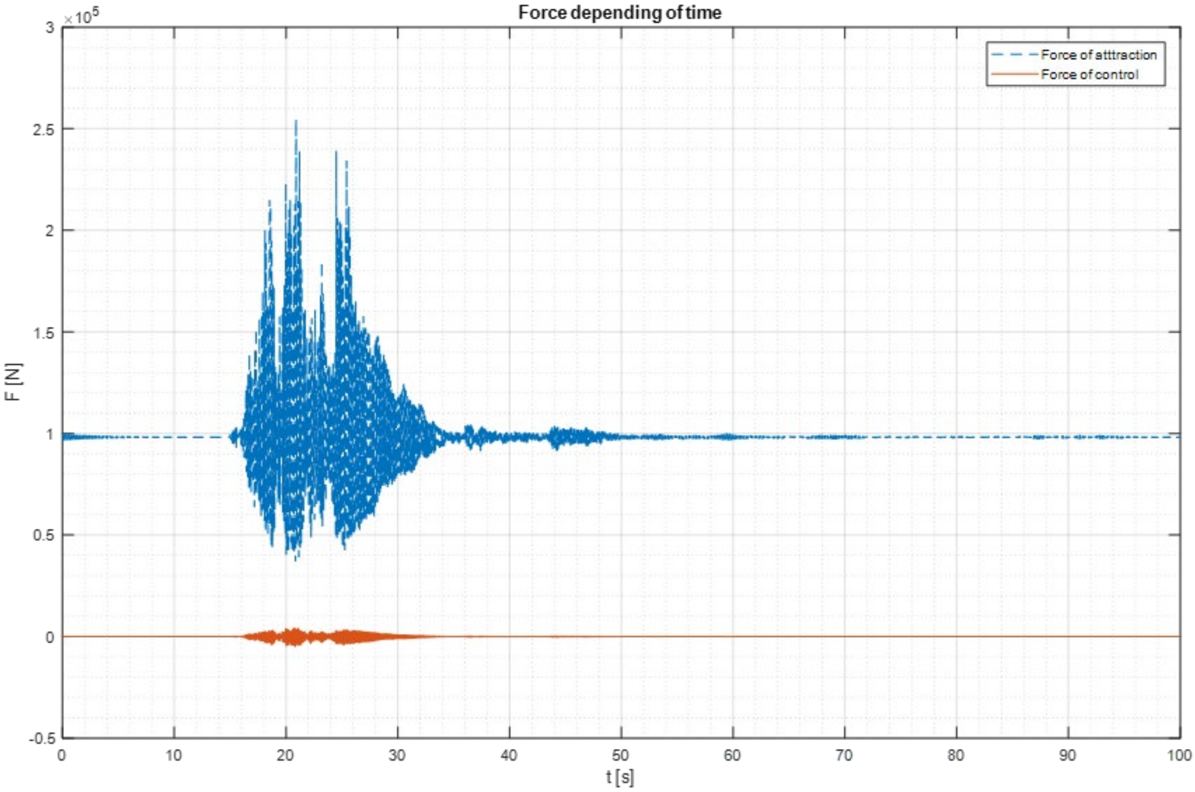
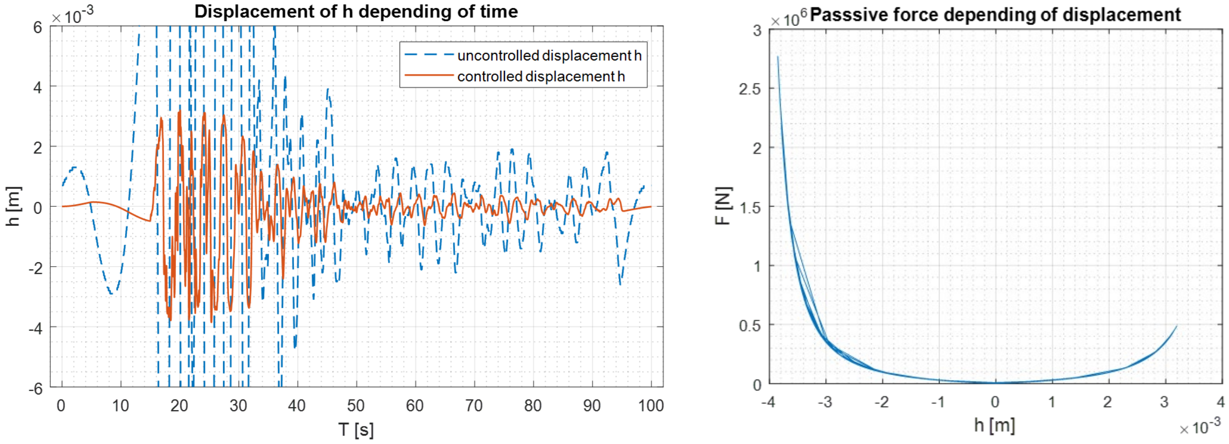


Figure 6: Comparing the changes of attraction force and control force over time.

Finally, Figure 7 shows the results of passive control simulation with α=100000 and n=10. Again, the vertical displacement are well controlled within the gap limit (-5mm,5mm), while the required force is within the range levitation force. This reults thus shows the feasibility of using permanent magnets to provide the resisitance force. Otherwise, seismic dampers (Golzar et al., 2018, Hazaveh et al., 2018b) could also be eligible for a more economical passive control without requiring additional external energy.



(a) (b)

Figure 7: Passive-control (a) compared to uncontrolled displacement, with (b) required control force

4 CONCLUSIONS

This paper provides a preliminary analysis of using active and passive control to ensure the vertical motion of a magnetic levitation house. The results indicate both PD controller and passive control might provide a good control of vertical displacement. The energy or power demand for both cases, particular for active control would be more realistic compared to power input and shift for the electromagnet levitation. The physical meaning or power quantity for the calculated control force remain to be determined in a future study, while this initial reulst justify the feasibility of conducting a further analysis and a small-scaled prototype set up in this novel field.

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