2008 American Control Conference
Westin Seattle Hotel, Seattle, Washington, USA
June 11-13, 2008

Modeling and Control of a Counter-Gravity Casting Machine

A. M. Khader, M. A. Abdelrahman, *Senior Member*, *IEEE*, Charles C. Carnal, and W. A. Deabes, *Student Member, IEEE*

***Abstract*— Counter-gravity casting is a process where molten metal is forced into the casting cavity against gravity. It aims at increasing the energy efficiency of the casting process. It also offers an opportunity of introducing automatic control into the process by changing the pressure under which the metal is forced into the mold cavity. This paper describes a new method of multi-variable control of the counter-gravity casting machine. System modeling of the counter-gravity machine reveals that it is a nonlinear system. The machine has been modeled as a set of linear systems corresponding to twelve regions of operation: six for increasing vacuum and six for decreasing vacuum. The models are parameterized based on the stem valve positions and the initial pressure in the casting vessel. The models are validated through actual data collected from the counter-gravity machine. An automatic controller is designed for control of the machine operation throughout the different regions. The full scheme of the controlled simulated machine consists of a valve selector and a gain scheduled controller based on the operating conditions of the machine. Simulations are provided to show the operation of the designed controller.**

***Index Terms*—Industrial Applications, Counter-gravity Casting**

I. INTRODUCTION

THE work HE work described in this paper is a continuation of work being carried out at Tennessee Tech University (TTU) for the development of a closed loop control of counter-gravity casting [1,2] for lost foam [3-5]. These results are obtained as part of an undergraduate research experience project at TTU. The counter-gravity machine shown in Figure 1 consists mainly of: a plenum to provide the necessary vacuum, a motor to suck the air, two pneumatic valves, one connected to the atmosphere and the other connected to the plenum (for vacuum) and two E/P transducers to control the position of both valve stems. The system is originally configured to work with a single controller where the 2 valves opening are linked together such that as one valve is opening, the other is closing. This model of operation is most problematic when operating in the range where both valves are open at the same time as it leads to a large drop in the plenum pressure. Moreover, in some operating conditions, an inert gas may be used in place of air in which case it would be needed to design a new controller to conserve that gas.

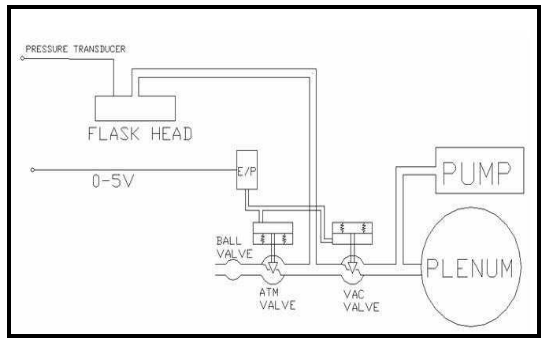

Fig. 1. Schematic diagram of counter-gravity machine with single controller.

A new scheme of control is proposed in which the two valves are operated independently. This adds another degree of freedom in the control of the pressure in the counter-gravity machine offering advantages in terms of faster system response and a constant plenum pressure [1].

The general system operates now in such a way that the atmospheric valve is shut and the vacuum valve is controlled, when more vacuum pressure is needed. The atmospheric valve is controlled and the vacuum is shut when more vacuum is needed. This switching between the 2 valves as the main controllers is what constitutes the bang-bang controller. So this is a special case of multivariable controller since one valve is being used at one time while the other valve is completely shut.

In the next sections of the paper, details of development of the controller are explained.

II. SYSTEM IDENTIFICATION

A. Collecting Data

An open loop system model for the counter-gravity machine was obtained through a series of step response tests for each of the valves. Thus, the most feasible way at the time was to collect data depending on a series of defined step

This work was supported by the National Science Foundation grant number EEC-0552860, Research Experiences for Undergraduates (REU) Industrial Applications of Sensing, Modeling, and Control at Tennessee Technological University, Cookeville, TN.

A.M. Khader is an undergraduate mechanical engineering student at Texas A&M University at Qatar, Doha, Qatar.

M. A. Abdelrahman is with the Electrical and Computer Engineering Department, Tennessee Technological University, Cookeville, TN 38505 USA (e-mail: mabdelrahman@tntech.edu).

C.C. Carnal is with the Electrical and Computer Engineering Department, Tennessee Technological University, Cookeville, TN 38505 USA (e-mail: CharlesLC@tntech.edu)

W. A. Deabes is currently a PhD student in Electrical and Computer Engineering Department, Tennessee Tech University, Cookeville, TN 38505 USA (e-mail: wadeabes21@tntech.edu).

inputs of different magnitudes, starting at different initial pressures in the vacuum camper (VC).

The Vacuum Valve Data: The Counter-gravity response to increasing vacuum was noted to a function of two variables: the valve stem position and the initial pressure in the VC. The system response is nonlinear and hence data were collected from different initial pressures for different valve stem positions. Table 1 shows the system states of both the valve and the vessel for recording different system responses for increasing vacuum.

As the system was based on the initial pressure in the vessel, as well as valve stem position, each valve stem position was tested for the range of different initial pressures. The position of the stem valve was measured using a position sensor installed on the stem for both valves. It should, also, be noted that the vacuum valve stem has a maximum displacement of 0.5 inch. The initial pressure is noted in terms of the sensor voltage reading with 1 V corresponding to atmospheric pressure and 5 Volts corresponding to the maximum pressure of approximately 350 inches of water.

TABLE 1
SYSTEM STATES AT WHICH THE SYSTEM RESPONSES WERE RECORDED FOR INCREASING VACUUM

Valve Stem Position (in)	Initial Vessel Pressure (Sensor Voltage Reading)
0.1	1,2,3,4,5
0.2	1,2,3,4,5
0.3	1,2,3,4,5
0.4	1,2,3,4,5
0.5	1,2,3,4,5

The Atmospheric Valve Data: A similar procedure was used to collect data for the atmospheric valve. However, it was used to move the vacuum from maximum to minimum. Data was collected by starting at different initial pressures and allowing the system to drain to zero vacuum. As the atmospheric valve was suffering from the same problems in the vacuum valve, the pressure was recorded as a function of the valve stem position collected from the position sensor.

Table 2 shows the valve stem position and initial vessel pressure used to study the system for decreasing vacuum. It should be noted that the atmospheric valve had a maximum opening of 0.35 inch.

TABLE 2
SYSTEM STATES AT WHICH THE SYSTEM RESPONSES WERE RECORDED FOR DECREASING VACUUM

Valve Stem Position (in)	Initial Vessel Pressure (Sensor Voltage Reading)
0.07	2, 3, 4, 5
0.14	2, 3, 4, 5
0.2	2, 3, 4, 5
0.27	2, 3, 4, 5
0.35	2, 3, 4, 5

B. System Modeling

System identification was carried out and a linear system model was obtained for the experimental data collected for both modes of operation. The atmospheric and vacuum valves stem position as the input and the pressure in the vacuum chamber as the output. First, second and third order models were obtained for each of the regions. As expected the model system appeared to be a better fit as the order increased. A first order model appears to capture the main dynamics of the system and was deemed enough for the modeling of the system dynamics.

The same testing was applied on all the other runs presented in Tables 1 and 2 and the results proved first order dominance as well. Thus, the machine was modeled as a set of linear first order transfer functions.

All the data were fitted smoothly in first order model except for the 0.1 inch step, for the vacuum valve. It is believed that this is caused by the close proximity of the valve gate to the seat, where the valve has a minute opening.

1) Vacuum Valve Modeling: The machine was run three times for the each of the conditions shown in Table 1. Each run was modeled into a transfer function, as described in the section above. Figure 2 shows the different transfer functions obtained for one of the runs for 0.5 inch valve stem position at different initial pressures. It should be noted that although the initial pressure is different for each plot in Figure 2, the plot always starts from zero as all the data were normalized before being used.

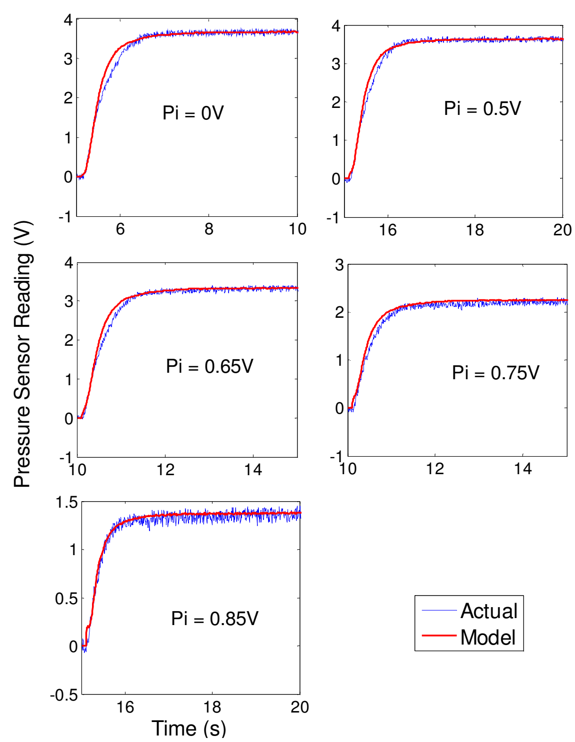

Fig. 2. The response of the model compared with the response of the actual system: 0.5 in vacuum valve stem position with different initial vessel pressures.

Through the study of the transfer functions determined from each experimental setup of the vacuum valve, as the ones provided through Figure 2, it was revealed that the system can be divided into three regions and each region would be divided into two sub-regions, i.e. a total of six distinct models can be used to fully describe the system response for increasing vacuum. Table 3 shows a summary of the conditions to separate the six regions developed to describe the increase in vacuum.

TABLE 3
SEPARATION OF SYSTEM RESPONSE AS A FUNCTION OF VALVE POSITION AND VESSEL PRESSURE

Valve Stem Position (x in inch)	Initial Vessel Pressure (y in sensor voltage reading)	Transfer Function Model
$x \leq 0.1$	$y \leq 3$	$H(s)=\frac{31.8}{1.18s+1}$
	$y > 3$	$H(s)=\frac{16}{0.4s+1}$
$0.1 < x \leq 0.3$	$y \leq 3$	$H(s)=\frac{13.1}{0.24s+1}$
	$y > 3$	$H(s)=\frac{6.25}{0.13s+1}$
$x > 0.3$	$y \leq 3$	$H(s)=\frac{8.33}{0.08s+1}$
	$y > 3$	$H(s)=\frac{5}{0.03s+1}$

The models shown in Table 3 were developed using a qualitative averaging procedure based on the transfer functions obtained for multiple experimental trials at each operating condition as provided in Table 1.

2) Atmospheric Valve Modeling:

Figure 3 shows the different transfer functions obtained for one of the runs for 0.2 inch valve stem position at different initial pressure levels in the vacuum chamber. It should be noted that although the initial pressure is different for each plot in Figure 3, the plot always starts from zero as all the data were normalized

Transfer functions that describe the system model were obtained for six different regions covering the full range of operation as the vacuum in the chamber is decreasing. These are summarized in Table 4. The reason why the models may seem not to fully acquire the same response as the actual system in Figure 3 is the need for a dual action to process the response: the vacuum valve needs to be open to install vacuum pressure in the system, once the pressure needs to be increased, the vacuum valve needs to be shut at the same time the atmospheric valve needs to be open. As a result, stickiness affected the original pressure data, thus affecting the final model. This problem was not encountered in modeling the increase in vacuum pressure, as shown in Figure 2.

The models developed in Table 4 were calculated using the same procedure to calculate the models in Table 3.

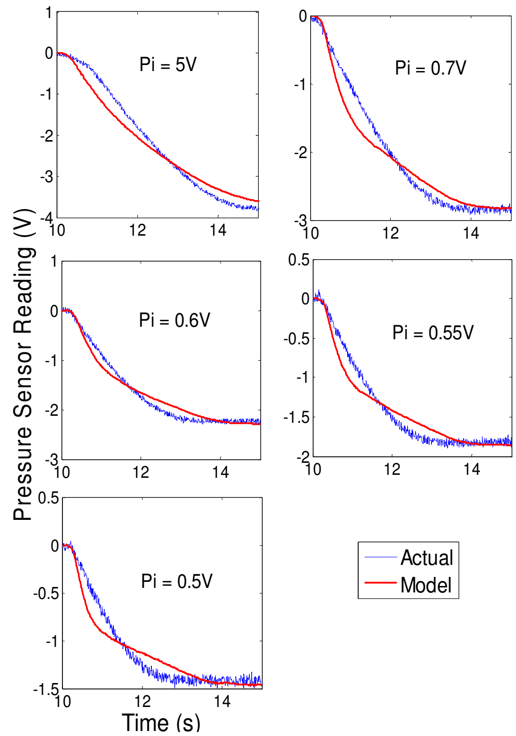

Fig. 3. Model and actual system response: 0.3in atmospheric valve stem position with different initial vessel pressures.

TABLE 4
SYSTEM MODELS AS A FUNCTION OF VALVE POSITION AND VESSEL PRESSURE

Valve Stem Position (x in inch)	Initial Vessel Pressure (y in sensor voltage reading)	Transfer Function Model
$x < 0.1$	$y \leq 3$	$H(s)=\frac{100}{2.5s+1}$
	$y > 3$	$H(s)=\frac{53.13}{0.63s+1}$
$0.1 \leq x \leq 0.275$	$y \leq 3$	$H(s)=\frac{12.5}{0.5s+1}$
	$y > 3$	$H(s)=\frac{90.09}{0.18s+1}$
$x > 0.275$	$y \leq 3$	$H(s)=\frac{5}{0.17s+1}$
	$y > 3$	$H(s)=\frac{2.27}{0.01s+1}$

C. *Model Validation*

The machine operation can be described by the set of transfer functions at the different operating conditions. As validation of the developed model through the entire range of operation, the complete model was tested throughout the entire operating range to observe transitions between different regions of operation. The physical machine was run to collect data for pressure with random movements of the vacuum valve and atmospheric valve stem positions. Figure 4 shows the actual pressure response, along with the positions of the vacuum valve stem and atmospheric valve stem.

Using the positions of the vacuum valve stem and the atmospheric valve stem collected from the position sensors (average values were used to remove noise and stickiness problems) as input to the developed models, the pressure profile was recorded, as shown in Figure 5.

Comparing the pressure profiles in Figure 4 and Figure 5, there appears to be small differences in some areas. It is to be noted that the model was run with one valve assumed to be shut when the other is operating; an idealized operation assumption (this is the sole important assumption for the model to work). However, this was not the case in the actual system, due to stickiness problems with both valves. Thus minor discrepancies between the actual and modeled profiles were developed. The stickiness already present in the valves may have lead to partially opened valves. These problems were not counted for in the simulation. The stickiness in the system, sometimes leads to simultaneous opening of both valves. Nevertheless, the simulated system does show the same major features as the actual system.

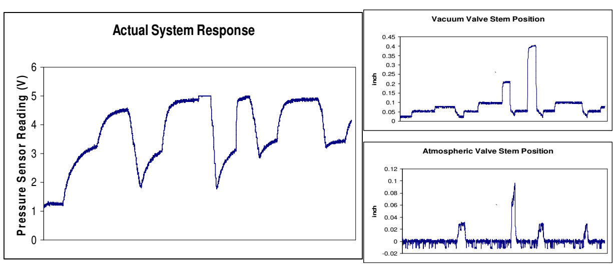

Fig. 4. The open loop response of the physical system.

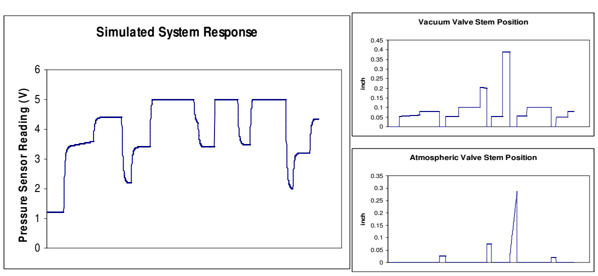

Fig. 5. The response of the simulated system with vacuum and atmospheric valve stems position as input.

III. System Control

The system was defined as 12 different regions. The approach we adopt here is to design a set of controllers to cover the different regions and design a gain scheduling procedure to switch among the controllers based on the direction of desired change in pressure, the stem valve position and the current pressure in the chamber [6].

A. *Defining the gains for each region*

To be able to control increasing vacuum, a PI controller was developed based on the first order models of the system. Each region was controlled separately based on the following design parameters: A rise time of 0.1s and maximum percent overshoot (Mp) of 5%.

The controller for each region was developed separately. The controller parameters for each region, for increasing and decreasing vacuum, are shown in Tables 5 and 6.

TABLE 5
CONTROLLER PARAMETERS FOR EACH REGION FOR INCREASING VACUUM

Transfer Function Model	Proportional Gain	Integral Gain
$H(s)=\dfrac{27}{s+0.85}$	0.9	12
$H(s)=\dfrac{40}{s+2.5}$	0.5675	8.1
$H(s)=\dfrac{55}{s+4.2}$	0.381	5.89
$H(s)=\dfrac{50}{s+8.0}$	0.344	6.48
$H(s)=\dfrac{100}{s+12}$	0.132	3.24
$H(s)=\dfrac{150}{s+30}$	1.48	216

TABLE 6
CONTROLLER PARAMETERS FOR EACH REGION FOR DECREASING VACUUM

Transfer Function Model	Proportional Gain	Integral Gain
$H(s)=\dfrac{40}{s+0.4}$	0.62	8.1
$H(s)=\dfrac{85}{s+1.6}$	0.277	3.81
$H(s)=\dfrac{25}{s+2}$	0.928	12.2
$H(s)=\dfrac{50}{s+5.5}$	0.394	15.6
$H(s)=\dfrac{30}{s+6}$	0.64	10.8
$H(s)=\dfrac{170}{s+75}$	1.04	190.5

Each region was tested separately to validate the design parameters of the controller. Figure 6 shows the controller pressure profile (top) compared with the desired pressure profile (bottom) for two models: (a) $H(s)=\dfrac{27}{s+0.85}$ on the left and (b) $H(s)=\dfrac{50}{s+8.0}$ on the right. These tests were carried out by simulating the conditions necessary for these models to function properly.

As shown in Figure 6 (a) and (b), the system responds quickly with a rise time of about 0.1s (as designed) at step inputs, with minimal overshoot (doesn't exceed 5%). Also, in response to a ramp reference signal, the system follows the profile smoothly. Next, the system needs to be tested in full (simulation of the whole machine) to be able to verify the actual system response.

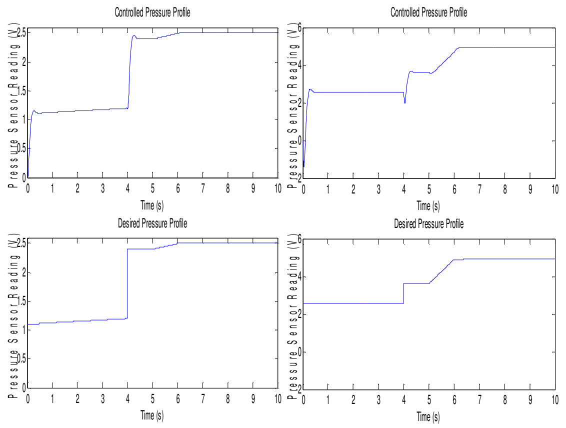

Fig. 6. The desired and the controlled pressure at two different regions: (a) First TF in Table 3 & (b) Fourth TF in Table 3

B. *Closed Loop Simulation*

It is worthy to note that the region selector developed in the simulator is a function of the initial pressure in the vessel and the desired position of the valve (which is a function of the vessel pressure). Mathematically, the selection (R) is described in Equation (1), as a function of pressure (P).

$$R = f(P[n-1], P[n]) \tag{1}$$

Thus, full machine simulation is needed to test the gains. Figure 7 shows a pressure profile along with the simulated controlled signal, using the gains in Table 5.

As shown in Figure 7, the control signal follows the pressure trajectory very closely. However, to validate the applicability of these controllers, different profiles need to be tested. Figure 8 shows the response to a fast change in the desired pressure levels.

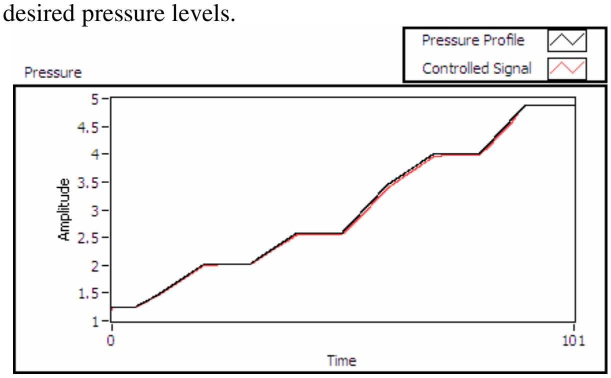

Fig. 7. Controlled simulation for ramped input functions

To examine full machine performance, both increasing and decreasing vacuum needed to be studied together. A valve selector is in charge of closing the appropriate valve depending on whether an increase or decrease in the vacuum is needed. Thus Figure 9 shows a simulated profile with increasing vacuum, then decreasing, where Figure 10 shows a simulated random profile including different magnitudes of increasing and decreasing vacuum.

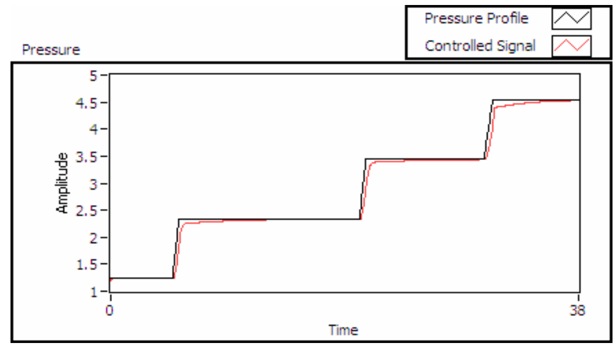

Fig. 8. Controlled simulation for a 0.5s span step input.

It is noted from Figure 9, that the simulated signal follows the profile very smoothly. The system does suffer from small undershoots, however it does not deem necessary to tweak the calculated gains. As for Figure 10, the control system proves to be of acceptable performance as it passes through eight of the 12 regions (which would be very typical for full machine operation).

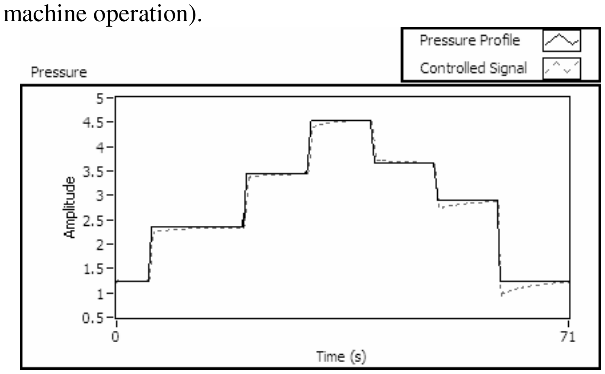

Fig. 9. Pressure profile and controlled simulation for increasing and decreasing vacuum.

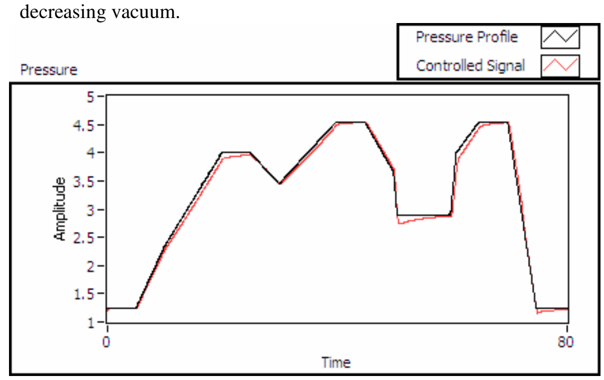

Fig. 10. Random profile with multiple increase and decrease in vacuum.

IV. Future Work

Problems in the valves such as stickiness can cause difficulties in the actual implementation of the controller to the counter-gravity system as can be seen in the model validation (Section II.C). A closed loop position controller for the valve stem position would help in alleviating these problems. Such controller has been designed and tested successfully at TTU and the integration of the two controllers on the actual machine would improve the performance of the implemented controller.

V. Conclusion

This paper presents an approach for controlling and modeling a counter-gravity casting machine through a 2-valve mode of operation. This mode of operation improves machine sensitivity and operability. The machine is modeled through a series of linear first order models representing twelve regions of operation: six regions for increasing vacuum and six regions for decreasing vacuum. The system model was validated through experimental data. A gain-scheduled controller and a valve selector are designed for operating the machine at the different operating conditions. The designed controller is tested through a simulation utilizing the validated model of the machine.

Acknoledgement

This work was supported by National Science Foundation grant number EEC-0552860 for Research Experience for Undergraduates.

REFERENCES

[1] http://www.hitchiner.com/HIMCO/Advantage.html. Jul 5, 2007. The Hitchiner Countergravity Advantage. 1-April-1998.

[2] University of Alabama Metal Casting Technology Center, spring 1995 newsletter. vol. 10, no 1

[3] E. Whitman, Control of a Counter-Gravity Machine. Tennessee Technological University, REU Industrial Applications of Sensing, Modeling and Control, August 2006.

[4] W. Deabes et al., Design and Implementation of a Control System for a Counter-Gravity Casting Machine. 39th Southeastern Symposium on System Theory, Macon, GA, 31207, March 4-6, 2007, p. 330 – 334.

[5] M. Davis, System Identification and Control of Counter Gravity Systems. Tennessee Technological University, REU Industrial Applications of Sensing, Modeling and Control, August 2006.

[6] D. Kukolj et al., Artificial intelligence based gain scheduling of PI speed controller in DC motor drives, Symposium on Industrial Electronics, 12-16 July 1999, p. 425 – 429

[7] W. J. Cui et al., Gain scheduling approach to excitation control in power systems, Journal of Tsinghua University, v 41, n 3, March, 2001, p 62-64

[8] G Franklin et al, Feedback Control of Dynamic Systems, Pearson Education, NJ 2006.

[9] Doug J. Leith et al., Survey of gain-scheduling analysis and design, International Journal of Control, vol. 73, n 11, Jul 20, 2000, pp. 1001-1025.