

**DEVELOPMENT OF A DIGITAL CONTROLLER FOR A
VERTICAL WIND TUNNEL (VWT) PROTOTYPE TO MITIGATE
BALL FLUCTUATIONS**

A Senior Scholars Thesis

by

RAMÓN ALEJANDRO SILVA

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

April 2010

Major: Mechanical Engineering

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Approved by:

Research Advisor:

Associate Dean for Undergraduate Research:

Won-jong Kim

Robert C. Webb

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ABSTRACT

Development of a Digital Controller for a Vertical Wind Tunnel (VWT) Prototype to Mitigate Ball Fluctuations. (April 2010)

Ramón Alejandro Silva
Department of Mechanical Engineering
Texas A&M University

Research Advisor: Dr. Won-jong Kim
Department of Mechanical Engineering

The objective of this research was to mitigate fluctuations of a levitated ping pong ball within a vertical wind tunnel (VWT) prototype. This was made possible by remodeling the VWT system with its inherent nonlinear characteristics instead of assuming constant parameter relationships. By considering these nonlinearities a more accurate model was developed that better represented the actual system. The *gain scheduling* controller technique was chosen to control the ball's vertical displacement within VWT prototype. After remodeling the VWT's dynamics, the transfer function gain, for three different specified equilibrium points, were found to be within $\pm 35\%$ of the original system dynamics' gain which explain why ball fluctuation was present. Also, three different controllers were developed to mitigate fluctuations at 0.10m, 0.15m and 0.20m. The three controllers were combined to create the gain scheduled controller; however, no testing has been done due to sudden, last minute hardware malfunction.

DEDICATION

This work is dedicated to those individuals who have continuously loved, influenced, and supported me throughout my life: my family and friends.

ACKNOWLEDGMENTS

First, I'd like to thank my mentor, Dr. Won-jong Kim, for his continuous help and guidance through the course of this project. Also, I'd like to acknowledge Ali Sadighi, Seungho Lee, and Changwon Kim who laid the foundation for my research with developing the framework of the Vertical Wind Tunnel (VWT) Prototype in the summer of 2008 and the Texas A&M University System Louis Stokes Alliance for Minority Participation (TAMUS LSAMP) who helped fund this project. Lastly, I'd like to acknowledge the Undergraduate Research Office for enabling undergraduate students, across all disciplines, to participate in such a unique learning experience.

NOMENCLATURE

ω	Angular Acceleration
A	Area
i_a	Armature Current
L_a	Armature Inductance
R_a	Armature Resistance
V_a	Armature Voltage
C_d	Coefficient of Drag
ζ	Damping Ratio
J_m	DC Motor Rotor Inertia
ρ	Density of Fluid
K_e	Electric Constant
g	Gravity
m	Mass
ω_n	Natural Frequency
K_t	Torque Constant
v	Velocity
VWT	Vertical Wind Tunnel

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CHAPTER I

INTRODUCTION

Skydiving is an activity involving a preplanned drop from a height using a deployable parachute. A typical jump involves individuals jumping out of an aircraft from approximately 4,000 meters (13,000 feet) in altitude and free-falling for a period of time before activating a parachute to decrease the skydiver's falling velocity. Once the parachute is opened, the jumper can control his or her direction and speed so that he or she can aim for the landing site and come to a relatively gentle stop in a safe landing environment. By manipulating the shape of the body—as a pilot manipulates the shape of his aircraft's wings—a skydiver can generate turns, forward motion, backwards motion, and even lift [1].

There are ways to practice different aspects of skydiving without actually jumping out of an aircraft. One option is using a vertical wind tunnel (VWT), as shown by Figure 1. This recreational pastime is frequently referred to as "indoor skydiving" and is a popular training tool for skydivers. By using large fans to produce wind speeds of approximately 120 mph, the terminal velocity of a falling human body belly-downwards, any individual can be maintained in midair simulating the sensation of actual skydiving [1].



Figure 1: Photograph of actual Vertical Wind Tunnel (VWT) [2]

In these VWT's various propellers and fans are connected to large diesel or electric motors that work together to move air through a column anywhere from 6 to 16 feet in diameter. Since the size, mass and skill level of flyers are different, it is necessary to control the air speed so that the flyer could be kept at a desired height. In the summer of 2008, Ali Sadighi et al. successfully created a vertical wind tunnel prototype, shown in Figure 2, to simulate the suspension of an individual in midair. This was done by creating a closed loop control system which used a small DC motor to generate air flow and a position sensor to monitor the ball's vertical location which, in turn, fed back to a microcontroller where a command signal was sent back to the DC motor after being amplified using a linear amplifier [1].

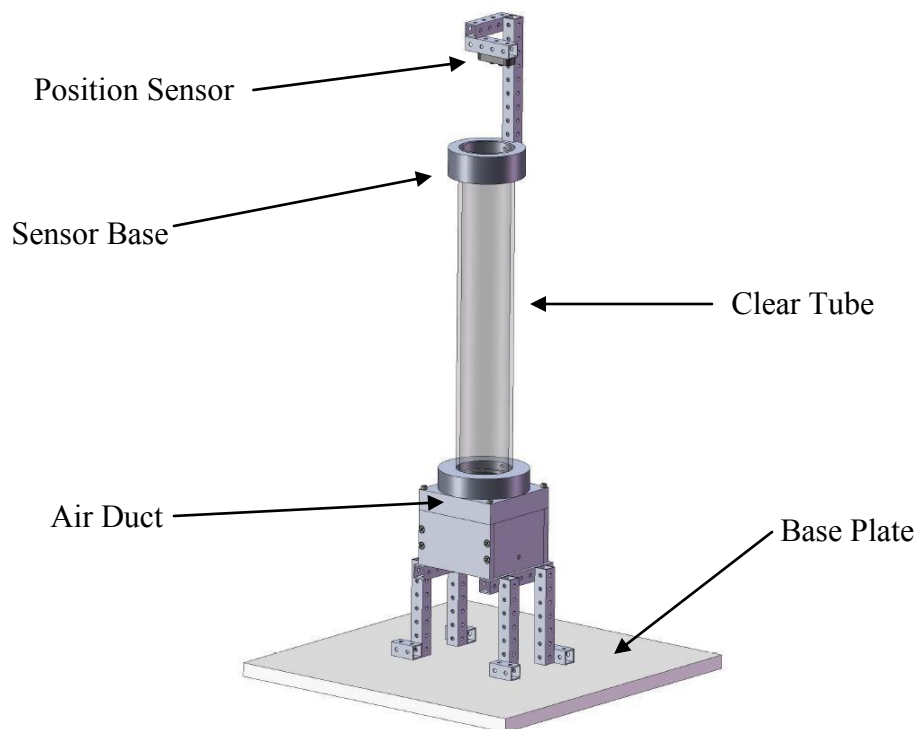


Figure 2: Component diagram of the Vertical Wind Tunnel (VWT) prototype [1]

Even though their setup proved to function relatively well the model used to characterize the system did not completely account for the nonlinear dynamics inherent to the system; as a result the ball "fluttered" around its specified vertical displacement. This was especially apparent when the levitated ball was held at heights greater than 17cm and less than 14cm. At these heights, the levitated ball would fluctuate between $\pm 1.5\text{cm}$ from the specified height compared to $\pm 0.5\text{cm}$ at heights between 14cm and 17cm. In order to simplify the model calculations of the system Ali et al. reasonably assumed that the angular velocity (ω) required to maintain the ball at a desired height was constant at all vertical positions within the clear tube. In truth however, angular velocity (fan speed) of

the fan does vary with vertical displacement and is not constant at all vertical position as Ali et al. believed.

This lays out the purpose of this research. In attempts to better control the levitated ball's position at heights greater than 17cm and less than 14cm a complete remodeling of system dynamics was done which incorporated the nonlinearities present within the system; which would then be used to develop a gain scheduled controller. With this more representative model and controller for the actual VWT prototype, it is expected that the relatively large fluctuations at those specified height will be mitigated.

CHAPTER II

METHODS

In order to better understand the overall result from this research, high-level summaries of key concepts, such as *feedback controls* and *gain scheduling controls*, are presented. These summaries are immediately followed by looking into the VWT's original modeling and controller setup. Lastly, the chapter will close with a clear description of how the remodeling of the system dynamics was conducted; in addition to how the gain scheduled controller will be constructed.

Feedback controls

Control of dynamic systems is a very common concept with many characteristics. A system that involves a person controlling a machine, as in driving an automobile, is called *manual control*. A system that involves machines only, as when room temperature can be set by a thermostat, is called *automatic control*. If the controller does not use a measure of the system output being controlled in computing the control action to take, the system is called *open-loop control*. If the controlled output signal is measured and fed back for use in the control computation, the system is called *closed-loop or feedback control* [3]. Both open and closed loop controls can be described using a graphical tool known as a *block diagram*, as shown in Figure 3.

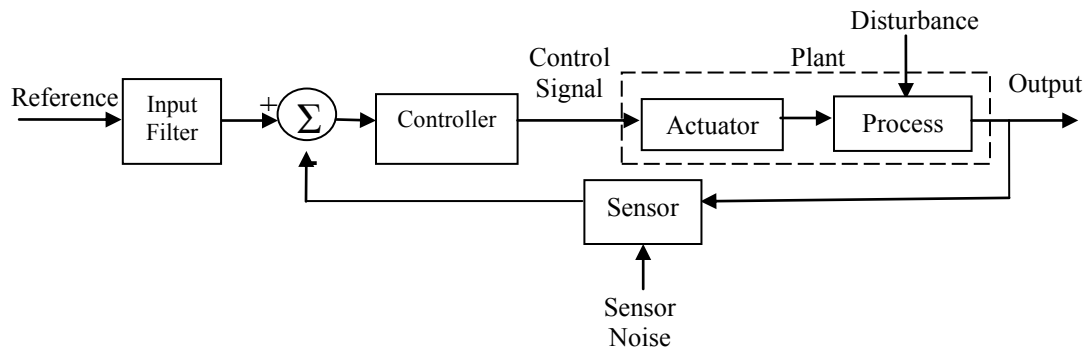


Figure 3: Component block diagram of an elementary feedback control [3]

In feedback systems the variable being controlled—such as temperature or speed—is measured by a sensor, and the measured information is fed back to the controller to influence the controlled variable. This principle is readily illustrated by a very common system, the household furnace controlled by the thermostat. Suppose both the temperature in the room where the thermostat is located and the outside temperature are significantly below the reference temperature (also called the set point) when power is applied. The thermostat will be *on*, and the control logic will open the furnace gas valve and light the fire box. This will cause heat Q_{in} to be supplied to the house at a rate that will be significantly larger than the heat loss Q_{out} . As a result, the room temperature will rise until it exceeds the thermostat reference setting by a small amount. At this time the furnace will be turned *off* and the room temperature will start to fall towards the outside value. When the temperature falls, a small amount below the set point, the thermostat will come *on* again and the cycle will repeat [3].

The central component of this feedback system is the *process* whose output is to be controlled. In the previous example, the process would be the house whose output is the room temperature and the *disturbance* to the process is the flow of heat from the house due to conduction through the walls and roof to the lower outside temperature. The *actuator* is the device that can influence the controlled variable of the process; in this case, the actuator is a gas furnace. The combination of process and actuator is called the *plant*, and the component that actually computes the desired control signal is the *controller*; while the thermostat serves as the *sensor* [3].

Similarly, a closed-loop control system was created for the VWT prototype where the *input* is the voltage that determines the fan speed; the *controller* is the root locus or the gain scheduled controller; the *plant* is the balls vertical position; and the *sensor* is the infrared sensor. A simplified block diagram for the VWT is shown in Figure 4.

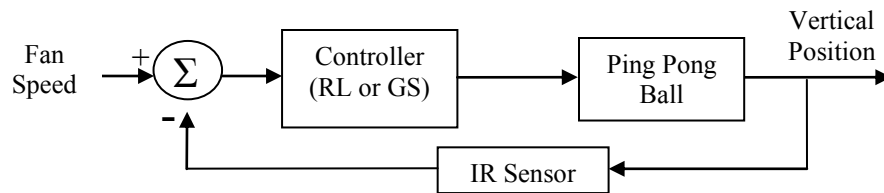


Figure 4: Simplified VWT prototype block diagram

Gain scheduling

In many situations, in order to simplify the controller's design the system's dynamics are *linearized*; however, the basic limitation of the design-via-linearization approach is the

fact that the controller is guaranteed to work only in some neighborhood of a single operating (equilibrium) point. One way to work around the limitations that come with linearization is *gain scheduling*. Gain scheduling is a technique that can extend the validity of the linearization approach to a range of operating points. In many situations, it is known how the dynamics of a system change with its operating points. It might even be possible to model the system in such a way that the operating points are parameterized by one or more variables, which are called *scheduling variables*. In such situations, we may linearize the system at several equilibrium points, design a linear feedback controller at each point, and implement the resulting family of linear controllers as a single controller whose parameters are changed by monitoring the scheduling variables; such controllers are called *gain-scheduled controllers* [4].

Original system dynamics and modeling

Before diving into the remodeling of the VWT prototype, we must first examine the system as presented by Ali et al. A schematic of VWT prototype is shown in Figure 5.

There are two vertical forces applied on the ping pong ball. One is the downward gravitational force and the other is upward drag force which are defined by the following equations [1]:

$$F_d = \frac{1}{2} \rho v^2 C_d A, \quad W = mg \quad (1)$$

where ρ is the air density, v is the air speed relative to the ball, C_d is the drag coefficient, A is the cross sectional area of the ball and m is the ball mass.

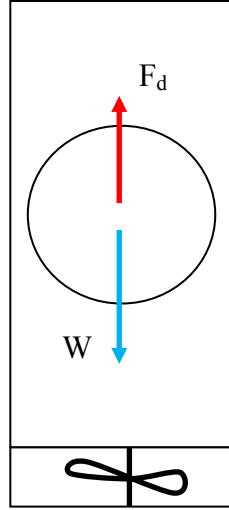


Figure 5: Schematic diagram of prototype wind tunnel [1]

Using the second Newton's law, the equation of motion (EOM) can be written as:

$$F = m\ddot{y} = \frac{1}{2}\rho v^2 C_d A - mg$$

$$\ddot{y} = Kv^2 - g, \quad K = \frac{1}{2m}\rho C_d A \quad (2)$$

Assuming that the air speed has a linear relationship with the fan speed (ω), the equation of motion will be:

$$\ddot{y} = \beta\omega^2 - g, \quad \beta = K\alpha^2 \quad (3)$$

As seen the above model is nonlinear. To be able to use classic control design methods such as root locus or frequency response, we have to linearize this model around its equilibrium point [1].

$$\beta W^2 - g = 0 \rightarrow W = \sqrt{\frac{g}{\beta}} \quad (4)$$

$$\begin{aligned} y &= Y + \hat{y}, \quad \omega = W + \hat{\omega} \\ \rightarrow \ddot{\hat{y}} &= \beta(W^2 + \hat{\omega}^2 + 2W\hat{\omega}) = \beta W^2 - g + \hat{\omega}^2 + 2\beta W\hat{\omega} \\ \ddot{\hat{y}} &= 2\beta W\hat{\omega} = 2\sqrt{\beta g}\hat{\omega} \end{aligned} \quad (5)$$

Now by taking the Laplace transform of this linearized model we will have [1]:

$$\frac{Y(s)}{\omega(s)} = \frac{2\sqrt{\beta g}}{s^2} \quad (6)$$

By modeling the DC motor we will derive the following equations:

$$J_m \dot{\omega} + b\omega = K_t i_a \quad (7)$$

$$L_a \dot{i}_a + R_a i_a = V_a - K_e \omega$$

By taking the Laplace transform of these equations, we will have [1]:

$$(J_m s + b)\omega = K_t i_a$$

$$(L_a s + R_a)I_a = V_a - K_e \omega$$

$$\frac{\omega(s)}{V_a(s)} = \frac{K_t}{J_m L_a s^2 + (b L_a + J_m R_a)s + (b R_a + K_t K_e)} \quad (8)$$

By combining equations (6) and (8):

$$\frac{Y(s)}{V_a(s)} = \frac{2\sqrt{\beta g} K_t}{s^2 (J_m L_a s^2 + (b L_a + J_m R_a)s + (b R_a + K_t K_e))} \quad (9)$$

In many cases the relative effect of the inductance is negligible compared with the mechanical motion and can be neglected. Hence,

$$\frac{Y(s)}{V_a(s)} = \frac{2\alpha \sqrt{K g} K_t}{s^2 (J_m R_a s + b R_a + K_t K_e)} \quad (10)$$

By substituting the following know values

$$K = 7.6(10^{-6}), \quad \alpha = 0.0882, \quad J_m = 1.26(10^{-6})kg.m^2$$

$$R_a = 3.65\Omega, \quad b = 5.8(10^{-6})\frac{Kg.m^2}{s}, \quad K_t = K_e = 0.013 \frac{N.m}{A}$$

the following simplified transfer function for the linear model of the system is obtained [1]:

$$\frac{Y(s)}{V_a(s)} = \frac{19.8}{s^2(4.6s + 190)} \quad (11)$$

Original controller design

Using the root locus method, Ali et al. created the system to have a settling time of 2.3sec and an overshoot less than 5%; as a result the damping ratio (ξ) of the closed loop poles and undamped natural frequency (ω_n) of dominant poles were chosen as [1]:

$$\xi = 0.8 \quad \omega_n = 2.5 \frac{rad}{sec}$$

To attain the set goals, the dominant closed loop poles were placed at $s = -2 \pm 1.5j$. Using the root locus approach, a lead/lead compensator was designed as [1]:

$$G(s) = 49.7 \frac{s + 0.92}{s + 6.8} \left(155.4 \frac{s + 0.92}{s + 6.8} \right) \quad (12)$$

From the frequency response of the compensated closed loop system the closed loop bandwidth was 4.173 rad/sec (0.664 Hz). Since the sampling frequency should be at least 20 times the closed loop bandwidth, the sampling frequency was taken to be 20 Hz, which made the discrete controller:

$$G(z) = \frac{43.46z - 41.5}{z - 0.7094} \quad (13)$$

Finally, the discrete control law for the implementation in C code would be [1]:

$$u[k + 1] = 0.7094u[k] + 43.46e[k + 1] - 41.5e[k] \quad (14)$$

Remodeling system dynamics

In order to better characterize the nonlinearities in the system, two relationships were found: voltage (V) vs. position (y) and angular velocity (ω) vs. voltage (V). Equation (15) denotes the quadratic relationship between voltage and position.

$$V = 4.2y^2 + 0.32y + 6.3 \quad (15)$$

Likewise, equation (16) denotes the linear relationship between angular velocity and voltage.

$$\omega = 52.4V - 9.7 \quad (16)$$

By combining (15) and (16) we obtain an expression relating position to angular velocity, as shown in equation (17).

$$\omega = 219.6y^2 + 16.9y + 319.9 \quad (17)$$

Using equation (17) we can then insert it back into equation (3) in order to define an EOM with a height dependent angular velocity which can be similarly linearized like the EOM for the original system dynamics and coupled with the DC motor, as well. Since a gain scheduled controller is desired, the system will be linearized at several equilibrium points and a controller, using the root locus method, will be created at each point in efforts of creating a family of linear controllers as a single controller whose parameter are changed by monitoring the scheduling variables.

With the new linearized EOM's at each desired equilibrium point, a controller can again be developed for each situation, such as the double pole/double zero compensator from

equation (12); which can then be put into the z-domain using the z-transform and find the discrete control law for the implementation in C code. From this point, the C code can be developed that specifies the scheduling variables and ties all the independent linear controllers into one robust control.

VWT circuit

Before any of the implementation was to be further explored, a new circuit board was built since the original Bluetooth wireless transmission module control malfunctioned and could not be repaired. Figure 6 shows a circuit diagram for the VWT.

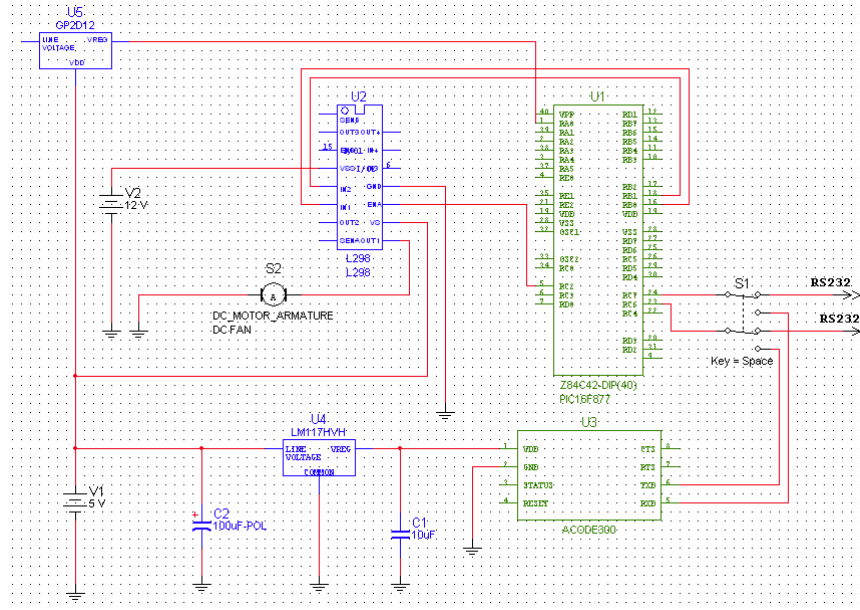


Figure 6: VWT electrical circuit [1]

Two main components that were used to build the circuit for the VWT prototype: the microcontroller (PIC16F877) and the motor driver (L298). The PIC16F877 is an 8bit microcontroller whose A0 port is used to receive analog input from the infrared sensor, the B1 port generates motor output signal to the L298, and C7 and C6 are used to receive and transmit data with the computer. Finally, the C2 port generates the PWM signal with 600 Hz [1].

The L298 motor driver IC is used to operate the DC fan. The L298 can be used up to a voltage of 46V with 4 amps. Since the DC fan only requires 12V, the L298 has no problem powering the fan. To implement the closed loop controller, the ball's position is measured by an infrared range sensor (GP2D12) [1].

CHAPTER III

RESULTS

Remodeling findings

In order to obtain a more accurate EOM, equation (17) is then inserted into equation (3) which then produces equation (18) shown below.

$$\ddot{y} = \beta\{1.4(10)^5 y^2 + 2.9(10)^7 y + 1.0(10)^5\} - g, \quad \beta = K\alpha^2 \quad (18)$$

where β represents a constant value which also incorporates constants K and α . The constant value K includes the same parameters as those shown in equation (2). To relate the DC motor's dynamics to this newly defined EOM shown in equation (18) we must get equation (18) in terms of angular velocity. This is done by solving the quadratic equation for y in equation (17); the solution is shown in terms of ω .

$$y = -3.84(10^{-2}) \pm \frac{\sqrt{-2.8(10^5) + 878.4\omega}}{439.2} \quad (19)$$

Once the solution for equation (19) is inserted back into equation (18) the newly defined EOM can be described as:

$$\ddot{y} = \beta \left\{ -1.22(10^6) + 640.46\omega + 6.63(10^4)\sqrt{-2.8(10^5) + 878.4\omega} \right\} - g \quad (20)$$

Equation (20) was linearized using Taylor Series Expansion which produced equation (21) below.

$$\ddot{y} = \beta \left\{ 640.46 + 2.91(10^7)(-2.8(10^5) + 878.4\Omega)^{-\frac{1}{2}} \right\} \hat{\omega} \quad (21)$$

To further simplify, the linearized equation was taken around its equilibrium point:

$$0 = \beta \left\{ -1.22(10^6) + 640.46W + 6.63(10^4) \sqrt{-2.8(10^5) + 878.4\Omega} \right\} - g$$

$$4.1(10^5)\Omega^2 + 3.87(10^{12})\Omega - 1.23(10^{15}) - \frac{g^2}{\beta^2} = 0$$

$$\Omega_0 = -4.72(10^6) \pm \frac{\sqrt{1.5(10^{25}) + 1.64(10^6) \frac{g^2}{\beta^2}}}{8.2(10^5)} \quad (22)$$

Which simplified equation (21) into:

$$\ddot{y} = \beta \{4.53(10^5)\} \hat{\omega} \quad (23)$$

Now by taking the Laplace transform of this linearized model we will have:

$$\frac{Y(s)}{\omega(s)} = \frac{\beta \{4.53(10^5)\}}{s^2} \quad (24)$$

By once again using the equations found from modeling the DC motor we can again obtain a transfer function relating vertical displacement and armature voltage. This is done by then coupling equation (8) and equation (24) and neglecting induction effects.

$$\frac{Y(s)}{V_a(s)} = \frac{4.53(10^5)K_t\beta}{s^2(J_m R_a s + b R_a + K_t K_e)} \quad (25)$$

After all the known values are again substituted into equation (25); the ending simplified transfer function considering the nonlinearities of the system is:

$$\frac{Y(s)}{V_a(s)} = \frac{25.07}{s^2(4.6s + 190)} \quad (26)$$

Three other equilibrium points ($\Omega_1, \Omega_2, \Omega_3$) were chosen to construct the gain scheduled controller. The corresponding vertical positions are $Y_1=0.10\text{m}$, $Y_2=0.15\text{m}$, $Y_3=0.20\text{m}$.

Using equation (19), Ω_1 was found to be 323.76 rad/sec; Ω_2 was 327.35 rad/sec; and Ω_3

was 332.02 rad/sec. Following the same procedures previously outlined, three additional transfer functions were derived for the corresponding vertical positions Y_1 , Y_2 , and Y_3 .

$$\begin{aligned}\frac{Y_1(s)}{V_a(s)} &= \frac{26.58}{s^2(4.6s + 190)} \\ \frac{Y_2(s)}{V_a(s)} &= \frac{19.54}{s^2(4.6s + 190)} \\ \frac{Y_3(s)}{V_a(s)} &= \frac{15.45}{s^2(4.6s + 190)}\end{aligned}\tag{27}$$

Control design

The original double pole/double zero compensator, from equation (12), was used as a base for the construction of the three new controllers at Y_1 , Y_2 , and Y_3 . For each newly defined plant transfer function a controller was designed to maintain the same overshoot and settling time requirements as the original lead compensator.

$$\begin{aligned}G_1(s) &= 49.7 \frac{s + 0.92}{s + 6.8} \left(116 \frac{s + 0.92}{s + 6.8} \right) \\ G_2(s) &= 49.7 \frac{s + 0.92}{s + 6.8} \left(157 \frac{s + 0.92}{s + 6.8} \right) \\ G_3(s) &= 49.7 \frac{s + 0.92}{s + 6.8} \left(199 \frac{s + 0.92}{s + 6.8} \right)\end{aligned}\tag{28}$$

Again, the three lead/lead compensators were converted into the z-domain that enabled the discrete control laws to be found for each equilibrium point, illustrated below.

$$\begin{aligned}G_1(z) &= \frac{101.4z - 96.86}{z - 0.7094} \\ G_2(z) &= \frac{137.3z - 131.1}{z - 0.7094}\end{aligned}\tag{29}$$

$$G_3(z) = \frac{174z - 166.2}{z - 0.7094}$$

Like the procedures for the original compensator, the discrete control laws were found to be:

$$\begin{aligned} u_1[k + 1] &= 0.7094u[k] + 101.4e[k + 1] - 96.86e[k] \\ u_2[k + 1] &= 0.7094u[k] + 137.3e[k + 1] - 131.1e[k] \\ u_3[k + 1] &= 0.7094u[k] + 174e[k + 1] - 166.2e[k] \end{aligned} \tag{30}$$

After obtaining the control laws, three distinct digital controllers were developed in C Code for the VWT. This code can be seen in the Appendix section of the report.

Presently, the coupling of the three individual controllers, for the gain scheduled controller, is still under construction. Also, due to unexpected hardware failure no testing has been conducted using these controllers to observe if the fluctuations are mitigated.

CHAPTER IV

SUMMARY AND CONCLUSIONS

Summary

Comparing equation (26) and (27), the linearized transfer functions that considers a height dependent fan speed, to equation (11), the original linearized transfer function with a constant fan speed; it is apparent why Ali et al. were able to produce reasonable performance from the VWT prototype. From the transfer functions all five equations have the same exact denominator and their corresponding gains range from 1.3% to 35% of each other, depending on the equilibrium position specified. Ali et al. assumed that because the clear tube was only 25cm in length, the air flow within the tube could be considered to be completely laminar, thus, the ball could be levitated at any vertical position with one constant fan speed. While this is a good exercise of their “engineering judgment” with only one specified gain fluctuations between $\pm 1.5\text{cm}$ from the desired position were present at heights less than 14cm and greater than 17cm. At vertical displacements between 14cm and 17cm the fluctuations seemed to be reduced to about $\pm 0.5\text{cm}$ from the desired height. These fluctuations were due to the fan spinning too fast for the lower positions and not quickly enough at the higher locations. It is also suspected that minor turbulent flow also develops at lengths greater than 17cm; however, more detailed experimentation would have to be done on the VWT’s clear tube. Due to these fluctuations a correlation between angular velocity (fan speed) and vertical displacement was empirically determined, which is shown by equation (17).

With this height dependent angular velocity, found in equation (17) the actual gain necessary to maintain a ping pong ball levitated at any point within the clear tube can be calculated. When the transfer function relating vertical displacement and armature voltage was derived using this height dependent fan speed, as shown in equation (27), as expected, the gain changed according to their corresponding height. From simple comparison we can see how at a vertical displacement of 15cm the gain for Y_2 is within 1.3% of the original gain with the constant fan speed assumption in equation (11). This would explain why the ball experienced relatively smaller fluctuations at this particular height. Similarly, when comparing the gain from Y_1 and Y_3 to the gain in equation (11) we see that the gain for Y_1 is about 35% larger while the gain for Y_3 is about 22% smaller than the gain in equation (11). This would explain why the ball seemed to fluctuate more at distances much higher and lower than 15cm.

Way forward & conclusions

Presently, the coupling for the complete gain scheduled controller using the discrete control laws provided by equation (30) is still under construction, thus, no actual testing has been conducted with these newly defined linear equations. This is due to unexpected hardware failure within the VWT's circuitry. However, it is expected that with these more accurate models of the system, at the specified equilibria of 0.10m, 0.15m and 0.20m, the fluctuations will be reasonably mitigated. Currently, the newly remodeled linear controllers have been converted into C code. Also, techniques are being explored

on how to parameterize and monitor the scheduling variables (equilibrium points) so that all three controllers can be controlled by monitoring the scheduling variables.

In closing, it is expected that the fluctuation of the levitated ping pong ball will definitely be mitigated using the models that incorporate the inherent nonlinear characteristics of the VWT; which will be validated by the gain scheduled controller.

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APPENDIX

A.1. Code

A.1.1. Timers [1]

Two timers are used in this system. First one is for sensor input sampling time, second one is used to generate PWM signal.

```
setup_timer_1(T1_INTERNAL | T1_DIV_BY_2);
```

Timer 1 is 16bit timer. Since internal clock works 2.5Mhz, overflow occurs at every

$$\frac{1}{2.5MHz} 2^{16} = 0.0262sec. \text{ Since the prescaler is set 2, timer1 sampling period is } 0.0262 \times 2 = 0.0524sec. \text{ Therefore, sampling frequency is } \frac{1}{0.0524} = 19.08 Hz$$

```
setup_timer_2(T2_DIV_BY_16,255,1); // 600Hz PWM
```

Timer 2 is 8bit timer. Since internal clock works 2.5Mhz, overflow occurs at

$$\text{every } \frac{1}{2.5MHz} 2^8 = 102.4\mu sec. \text{ Since the prescaler is set by 16, timer1 sampling period is } 102.4 \times 10^{-6} \times 16 = 0.0016sec. \text{ Therefore, sampling frequency is } \frac{1}{0.0016} = 610.35 Hz$$

A.1.2 Interrupts [1]

RS232 Receive interrupt and timer interrupt are used. RS232 Receive interrupt is required to change. Reference is changed by designated key.


```

reference input. #INT_RDA
RS232C_Receive_Interrupt()
{
switch(input from keyboard or wireless controller){
    case('designated key') : change reference
        default :
}

```

A.1.3 Internal functions [1]

A.1.3.1 Position sensing

This function converts feedback voltage to corresponding distance. Datasheet from manufacture is referred for calculation.

```

float v2d(sensed input voltage)
{

$$ball\ position = \frac{(sensed\ voltage - 0.4)}{0.05}$$

return ball position;
}

```

<Pseudo code to calculate ball position>

A.1.3.2 Real time control

In this function, digital controller is implemented.

```
float control(float pos, float ref)
{
    err=ref-pos;

    //controller for Y1 equilibrium point
    con_input=0.7094*con_input_prev + 101.4*(err/100) – 96.86*(err_prev/100);

    //controller for Y2 equilibrium point
    //con_input=0.7094*con_input_prev + 137.3*(err/100) – 131.1*(err_prev/100);

    //controller for Y3 equilibrium point
    // con_input=0.7094*con_input_prev + 174*(err/100) – 166.2*(err_prev/100);

    err_prev=err;          // back up
    previous data
    con_input_prev=con_input;
    return (con_input);
}
```

<Pseudo code to generate control input>

A.1.3.3 PWM signal

Since fan angular velocity is determined by PWM duty ratio, the determined control input from digital controller should be converted to corresponding duty ratio. The duty ratio is assumed to linear from 10 to 1030. However, by experiment, duty ratio is not consistent through entire working range. Therefore, desirable duty ratio is determined in two cases. When reference input is lower than 12cm, it required smaller dc maintain voltage then higher reference input.

```
long v2duty(float con_input)
{
    if(ref<=12) duty=120.32*(con_input+6.05)-162.29;
    else duty=120.32*(con_input+6.3)-162.29;
    return duty;
}
```

<Pseudo code determine duty ratio>

The complete code is below [1]:

```
#include <16F877.h>

#include <math.h>

#define delay(clock=10000000)

#define rs232(baud=9600, xmit=PIN_C6, rcv=PIN_C7)

long duty=750;
```

```

long count=0;

float con_input=0;

float con_input_prev=0;

float reflect_volt=0;

float ref=10; // initial reference 10cm from bottom

float pos=0;

float err=0;

float err_prev=0;

float v2d(float reflect_volt);

float control(float pos, float ref);

long v2duty(float con_input);

////calibration parameters ///

float sen_cal=50;

////////////////////

#INT_TIMER1

Timer1_Interrupt(){

reflect_volt=read_adc();

reflect_volt=reflect_volt/sen_cal; // calibration of sensor;

pos=v2d(reflect_volt);

con_input=control(pos,ref);

duty=v2duty(con_input);

set_pwm1_duty(duty);

printf("Ref Volt:%f, Ball:%f ,Err:%f , ref_pos:%f , duty:%lu\n\r",reflect_volt,pos,err,ref,duty);

}

```

```

#INT_RDA

RS232C_Receive_Interrupt()

{
    char rx;

    count++;

    rx=getc();


    switch(rx){

    case('e') : OUTPUT_B(0x01);

    set_pwm1_duty(duty);

    printf("Motor On \n\r");

    enable_interrupts(INT_TIMER1);

    break;

    case('x') : OUTPUT_B(0x00);

    printf("STOP\n\r");

    disable_interrupts(INT_TIMER1);

    break;


    case('z'): {disable_interrupts(INT_RDA);

    printf("Switch mode...\n\r");

    delay_ms(3000);

    enable_interrupts(INT_RDA);}

    break;


    case('j'): ref=ref+1;

    break;

```

```
case('k'): ref=ref-1;
```

```
break;
```

```
case('s'): ref=1;
```

```
break;
```

```
case('a'): ref=5;
```

```
break;
```

```
case('w'): ref=9;
```

```
break;
```

```
case('d'): ref=20;
```

```
break;
```

```
case('m'): ref=10+9*sin(3.14*(count*0.05));
```

```
break;
```

```
default :
```

```
}
```

```
}
```

```
#PRIORITY RDA, TIMER1
```

```
void inst()
```

```
{
```

```
OUTPUT_B(0x01);
```

```
duty=550;
```

```

set_pwm1_duty(duty);

printf("ON:'e' , OFF:'x' , Speed Up:'k' , Speed Down:'j' \n\r");
}

float v2d(float reflect_volt)
{
pos=(reflect_volt-0.4)/0.05;
return pos;
}

float control(float pos, float ref)
{
err=ref-pos;

//controller for Y1 equilibrium point
con_input=0.7094*con_input_prev + 101.4*(err/100) – 96.86*(err_prev/100);

//controller for Y2 equilibrium point
//con_input=0.7094*con_input_prev + 137.3*(err/100) – 131.1*(err_prev/100);

//controller for Y3 equilibrium point
// con_input=0.7094*con_input_prev + 174*(err/100) – 166.2*(err_prev/100);

err_prev=err;
con_input_prev=con_input;
return (con_input);
}

```

```

long v2duty(float con_input) //5.97v -> 530 (start )
{
  if(ref<=12) duty=120.32*(con_input+6.05)-162.29;
  else duty=120.32*(con_input+6.3)-162.29;
  if(duty<=800) duty=duty*1;
  else duty=800;
  return duty;
}

void main()
{
  enable_interrupts(INT_RDA);
  enable_interrupts(GLOBAL);
  setup_port_a(ALL_ANALOG);
  setup_adc(adc_clock_internal);
  set_adc_channel(0);
  setup_ccp1(CCP_PWM);
  setup_timer_1(T1_INTERNAL | T1_DIV_BY_2); // Sampling frequency 19Hz
  setup_timer_2(T2_DIV_BY_16,255,1); // 600Hz PWM
  inst();

  while(1)
  {

  }
}

```


CONTACT INFORMATION

Name: Ramón Alejandro Silva

Professional Address: c/o Dr. Won-jong Kim
Texas A&M University
Department of Mechanical Engineering
3123 TAMU
College Station, TX 77843

Email Address: rsilva06@tamu.edu

Education: B.S., Mechanical Engineering,
Texas A&M University, May 2010
Undergraduate Research Scholar