DEVELOPMENT OF A MICRO-CONTROLLER INTERFACE AND PROPORTIONAL-INTEGRAL-DERIVATIVE CONTROL PROGRAM FOR A LOWER BODY NEGATIVE PRESSURE CHAMBER USING VARIOUS ENVIRONMENTAL VARIABLES AS CONTROL INPUTS

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Abstract

One purpose of Lower Body Negative Pressure (LBNP) chambers is to simulate the transition from microgravity to Earth-gravity. Physiological tests are conducted to assess stresses upon the cardiovascular system during these simulations. In general, the internal negative air-pressure of LBNP chambers is controlled with a proportional control system using only air-pressure as input. This can lead to an uncomfortable environment for the test subject. The proposed LBNP chamber uses a proportional integral derivative control program, which uses temperature, humidity and airflow in addition to the traditional air-pressure as inputs. These proposed additional parameters would serve to better control the internal environment of the LBNP chamber.

Key Words
Control Systems, Lower Body Negative Pressure Chamber, Aerospace Medicine

1. Introduction

Lower Body Negative Pressure (LBNP) chambers have been used for the past 30 years to "test orthostatic tolerance on Earth, and as a countermeasure during spaceflight to prevent post flight orthostatic intolerance" [1]. LBNP chambers can also be used to simulate the transition from the microgravity conditions of Space to the normal gravity conditions of Earth (the subject experiences hypergravity, i.e. >+1G). During a simulation, the subject lies on her/his back and the lower body is contained within the LBNP chamber. The chamber is air-sealed with a rubber skirt around the waist of the subject. The pressure within the chamber is lowered, and blood is displaced into the lower body, consequently putting stress upon the cardiovascular system. Levels of negative air-pressure and length of exposure vary depending on the protocol being followed. The µG Lab (Microgravity Laboratory) has developed a protocol that ramps from 0 mmHg to -2.5 mmHg to -15 mmHg to -30 mmHg and finally to -45 mmHg with a constant time between each change in pressure set at 7 minutes. This protocol is an adaptation of the protocol used by the Institute of Aerospace Medicine of the German Aerospace Center.

Currently, the µG Lab has a functioning LBNP chamber that uses a simple proportional control program to maintain the desired negative air-pressure within the chamber, which was developed in co-operation with the Institute of Aerospace Medicine of the German Aerospace Center, Cologne, Germany. This is, in general, the de facto control method for maintaining interior negative air-pressure of LBNP chambers.
There are two main problems with this method of control. The first problem is that the proportional control system is under damped with a large maximum overshoot and a relatively long settling-time. This problem could be addressed by using a PID (proportional integral derivative) control system. The overall anticipatory effect of integral-plus-derivative control action can be used to eliminate steady-state error and decrease rise time, while diminishing both maximum overshoot and settling time.

The second problem occurs during the transitional simulations. The subject is often required to perform exercise within the LBNP chamber. The exercise, using a cycle ergometer, can cause the LBNP chamber to heat up and to become more humid. This is not only an uncomfortable environment for the subject it also modifies the cardiovascular system response. For these reasons the µG Lab has undertaken the development of a new control system for its existing LBNP chamber.

2. Methodology

A. Changes made to the existing LBNP chamber

The new system will use a PID control program written in Simulink that uses various environmental variables as input. Physical modifications of the LBNP chamber are required to acquire the various environmental sensor readings. The outlet valve is now a T-connection. Air is output through the vacuum pump and as well to the external environment by a direct connection. The connection to the external environment can now be opened or closed by a second stepper motor. The modification to this valve should enable the control of airflow into the chamber. It is proposed to control the temperature and humidity within the chamber, by controlling airflow. An airflow sensor (a Pitot tube using two pressure transducers) has been added at the inlet valve, as have temperature, humidity and air-pressure sensors within the chamber. In order to connect the PID control program to the various sensors a new interface program has been written for the ADuC812 micro-controller. The micro-controller is used as an A/D converter and to transmit control data to the two stepper motors that open and close the two valves to the exterior environment of the LBNP chamber.

B. Sensors and ADuC812 micro-controller interface

The interface program between the sensors, motors and Simulink was written in C with inline assembly. Using a SDCC (Small Device C Compiler) the code was compiled and then translated into assembly language and downloaded to an ADuC812 micro-controller. The ADuC812 micro-controller periodically samples the analogue readings of each sensor and sends the 12-bit digitally converted value to the communication interface in Simulink on a Windows PC via the UART Serial Port using the RS232 protocol. It specifies which type of reading it is sending by sending a one-byte header and then, by breaking up the 12-bit value into two, it sends two bytes of data for each reading. The communication interface in Simulink identifies the headers and directs the inputs to the PID control program in Simulink, which will then send control data back to the micro-controller using the same communication methods as above. The byte that is sent is formatted so that the two most significant bits make up a header identifying whether the 6-bit value that follows is the number of steps to open or close motor1 or motor2. The ADuC812 micro-controller identifies which motor the data is intended for and in which direction to turn the motor, and then via a digital port instructs that motor to turn the number of steps indicated by the six least significant bits of the byte.

C. Sensors and Simulink interface

Part of the interface program is in Simulink. Using the RS232 protocol, Simulink receives the sensor readings
from the ADuC812 micro-controller. These digitally converted values are numbers between 0 and 4095 (12 bit A/D converter, $2^{12} = 4096$) and they needed to be calibrated to reflect physically meaningful values with units. To calibrate each sensor, several values were taken at known points (i.e. using a digital thermometer and manometer for comparisons). These points were then graphed to confirm that the sensor’s outputs were linear within the working range. As they all were, using the known interception points and the slope from the graph, equations were written. When Simulink receives these digital readings it uses them as input into these equations and the output represents air-pressure in mmHg, temperature in degrees Celsius, humidity as a percentage and airflow in m/s.

**D. PID control program in Simulink**

The proposed PID program is a modification of the standard PID model in the Simulink Control Systems Toolbox library of the form shown in Figure 2, where $K_p$ is the proportional gain, $T_i$ is the integral time, $T_d$ is the derivative time and $S$ is the Laplace transform.

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**Figure 2: PID Control System**

There will be two PID controller loops, one to control air-pressure and the other to control temperature and humidity by controlling airflow. The first step was to create and tune the PID controller for the air-pressure. The second step will be to measure different temperature and humidity combinations and empirically find the temperature and humidity to airflow relationship required to be able to use airflow to control temperature and humidity within the LBNP chamber.

For both PID controllers, because the vinyl walls of the LBNP chamber do not expand/shrink linearly as the pressure changes, the system is too complex to model mathematically. Thus, an experimental approach to tuning the PID controllers was adopted [2]. A common method, first proposed by Ziegler and Nichols in 1942, gives rules for determining values of the proportional gain, $K_p$, integral time, $T_i$, and the derivative time, $T_d$ [3]. The proposed method is known as the Ziegler-Nichols Tuning rule based on Critical Gain, $K_{CR}$ and Critical Period, $P_{CR}$ and is sometimes called the Second Ziegler-Nichols Method. First the parameters are set: $T_i = \infty$ and $T_d = 0$. Then, using only the proportional control part of the PID control program, as seen in Figure 3, $K_p$ is increased from 0 until the output first exhibits sustained oscillations, the critical value $K_{CR}$. The period of the oscillations when the critical value is recorded is called the critical period, $P_{CR}$.

Using the settings suggested by Ziegler and Nichols shown in Table 1, $K_p$, $T_i$ and $T_d$ can be found using $P_{CR}$ and $K_{CR}$.

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**Table 1 Ziegler-Nichols Tuning Rule Setting Suggestions**

<table>
<thead>
<tr>
<th>Controller</th>
<th>$K_p$</th>
<th>$T_i$</th>
<th>$T_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>$0.5K_{CR}$</td>
<td>$\infty$</td>
<td>0</td>
</tr>
<tr>
<td>PI</td>
<td>$0.45K_{CR}$</td>
<td>$P_{CR}/1.2$</td>
<td>0</td>
</tr>
<tr>
<td>PID</td>
<td>$0.6K_{CR}$</td>
<td>$0.5P_{CR}$</td>
<td>$0.125P_{CR}$</td>
</tr>
</tbody>
</table>

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**3. Results**

At this point in the project the ADuC812 micro-controller interface program is completed and fully functional. The Simulink portion of the interface is completed and functional, delivering calibrated sensor readings to the PID control program in Simulink. The air-pressure PID controller has been tuned using the Ziegler-Nichols method as described in the above section. Those PID parameters, which can be seen in Table 2, achieved a very fast rise-time (averaging less than 3 seconds) and nearly no steady-state error. However, this was at the cost of a large maximum overshoot (averaging at 60%) and a slow settling-time (averaging between 15-20 seconds). Finer tuning was completed by keeping in mind that settling-time and maximum overshoot can be reduced by increasing $T_d$ and decreasing $T_i$. The PID values that were finally chosen can be seen in the second half of Table 2.

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**Table 2 Ziegler-Nichols calculated PID parameters and retuned final PID parameters**

<table>
<thead>
<tr>
<th>Pressure (mmHg)</th>
<th>Calculated PID Parameters</th>
<th>Re-tuned PID parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_p$</td>
<td>$T_i$</td>
</tr>
<tr>
<td>-2</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>-15</td>
<td>180</td>
<td>2.5</td>
</tr>
<tr>
<td>-30</td>
<td>150</td>
<td>2.5</td>
</tr>
<tr>
<td>-45</td>
<td>48</td>
<td>3</td>
</tr>
</tbody>
</table>

Preliminary tests show that the PID control program maintains the desired air-pressure. The μG LBNP chamber protocol was manually followed and the results can be seen in Figure 4. The fine tuning of the PID parameters resulted in a decrease of the maximum overshoot from an average of 60% to an average of 8% and a decrease in the settling-time from averaging between 15 – 20 seconds to averaging between 5 - 10 seconds.
We are now in the process of taking measurements to determine the temperature, humidity and airflow relationship. A GUI (Graphical User Interface) has been built in Matlab. This GUI allows the user to input reference air-pressure, temperature and humidity values.

4. Discussion

The objectives of this project were: to make a new interface program for the ADuC812 micro-controller, and to create a new PID control program, that uses as input various environmental sensors. The interface program, partially written in assembly language (C using SDCC) for the micro-controller and the second part, written in Simulink is complete and has been shown to work properly. Various attempts were made to create a hand-shaking protocol to be used on the UART Serial Port between Simulink and the ADuC812 micro-controller. However, problems with the synchronization of the two different clocks occurred and it was found that the RS232 Receiving buffer in Simulink was slow and data was often lost. In the end the method that was found to work the best was to periodically send the A/D converted sensor readings, rather then wait for Simulink to ask the ADuC812 micro-controller to send them.

Although the air-pressure sensor was already calibrated from a previous experiment, changing the other digital sensor readings into physically meaningful values took more time then expected. The humidity and temperature sensors were fairly straightforward as they are standard transducers, with linear output. However, the airflow sensor is actually made up of two air-pressure transducers configured along a hose in the manner known as a Pitot Tube [4]. Airflow is calculated using Bernoulli’s Equation [5]. To calibrate this, both air-pressure transducers had to be calibrated and then tuning had to be done, by making comparisons to a digital airflow meter in order to change the air-pressure into air-velocity.

The PID controller that controls the air-pressure within the LBNP chamber has first been tuned using Ziegler-Nichols second method and then finely tuned using knowledge of PID parameters characteristics. Preliminary tests using the µG LBNP chamber protocol adapted from the German Aerospace Center’s LBNP chamber protocol have shown that the PID is working in the under damped region with a very small overshoot, fast rise time and small settling time. The next step will be to compile the data required to create an empirical relationship between the temperature, humidity and required airflow to maintain these parameters as a desired constant. Once this relationship is found, it can be used to create a reference value for the airflow in the separate second PID control loop. Thus, air-pressure, temperature and humidity will be maintained by changing airflow into and out of the LBNP chamber.

5. Conclusion

In general, LBNP chambers that are being used in aerospace medicine research have single-input proportional controllers, using air-pressure as the input. If the subject is required to perform exercise within the LBNP chamber they can become uncomfortable due to the increase in heat and humidity. The proposed and partially developed µG Lab LBNP chamber will use additional environmental parameters to control the internal LBNP chamber environment. The additional environmental sensors and second valve were added to improve the comfort of the subject within the LBNP chamber during an experiment. The new sensors, valve, stepper motor and assembly/Simulink Interface programs have been added and successfully calibrated. The PID controller that controls air-pressure has been tuned and shown to work successfully. It is proposed that when the multi-input (two loop) PID control program is fully functioning, a subject will be able to participate in experiments in greater comfort than experienced in the standard LBNP chambers currently in use.

Once the airflow PID controller in the µG LBNP chamber have been tuned the next step will be to add a section to the Simulink communications interface, that will be controlled by the GUI, that will put into effect the microgravity to normal gravity transition simulation protocol devised by the German Aerospace Center and adapted by the Microgravity Laboratory at PUCRS. This will require the use of the Real-time toolbox in Matlab. The protocol specifies different negative air-pressures to be used for specific lengths of time. The protocol also specifies a method to make emergency stops in the event that the subject undergoes pre-syncope or cardiac arrhythmia. Thus an emergency stop function will be added to the Simulink software and a physical emergency stop button will be added to the micro-controller hardware. Once all of these additions are made the µG LBNP chamber will be a much safer, accurate and
comfortable LBNP chamber than those currently being used in aerospace medicine research.

References


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i Presyncope is the condition that occurs before loss of consciousness resulting from insufficient blood flow to the brain, which includes as symptoms: dizziness and blurred vision.

ii Arrhythmia is an alteration in rhythm of the heartbeat either in time or force.