Mock Circulatory Loop Compliance Chamber Employing a Novel Real-Time Control Process

Charles E. Taylor

e-mail: taylorce@mymail.vcu.edu

Gerald E. Miller

e-mail: gemiller@vcu.edu

Department of Biomedical Engineering,
Virginia Commonwealth University,
401 West Main Street RM1229,
Richmond, VA 23220

The use of compliance chambers in mock circulatory loop construction is the predominant means of simulating arterial compliance. Utilizing mock circulatory loops as bench test methods for cardiac assist technologies necessitates that they must be capable of reproducing the circulatory conditions that would exist physiologically. Of particular interest is the ability to determine instantaneous compliance of the system, and the ability to change the compliance in real-time. This capability enables continuous battery testing of conditions without stopping the flow to change the compliance chamber settings, and the simulation of dynamic changes in arterial compliance. The method tested involves the use of a compliance chamber utilizing a circular natural latex rubber membrane separating the fluid and air portions of the device. Change in system compliance is affected by the airspace pressure, which creates more reaction force at the membrane to the fluid pressure. A pressure sensor in the fluid portion of the chamber and a displacement sensor monitoring membrane center deflection allow for real-time inputs to the control algorithm. A predefined numerical model correlates the displacement sensor data to the volume displacement of the membrane. The control algorithm involves a tuned π loop maintaining the volume distention of the membrane via regulation of the air space pressure. The proportional integral (PI) controller tuning was achieved by creating a computational model of the compliance chamber using SimulinkTM Simscape[®] toolboxes. These toolboxes were used to construct a model of the hydraulic, mechanical, and pneumatic elements in the physical design. Parameter EstimationTM tools and Design OptimizationTM methods were employed to determine unknown physical parameters in the system, and tune the process controller used to maintain the compliance setting. It was found that the resulting control architecture was capable of maintaining compliance along a pressure-volume curve and allowed for changes to the compliance set point curve without stopping the pulsatile flow. [DOI: 10.1115/1.4007943]

1 Introduction

1.1 Background. Mock circulatory loops are integral to the *in vitro* evaluation of cardiac assistance technologies. Designs typically employed utilize a lumped parameter approach to simulating physiological conditions. The flow of the mock circulatory loop progresses serially through separate devices, with each simulating a parameter of the circulatory system. The mock circulatory loop that was employed in this investigation was a systemic circulation simulator; left ventricle pump, arterial compliance chamber, total peripheral resistance device, and a venous reservoir. The pump providing the left ventricular simulation is a Harvard Apparatus

Model 1423 Large Animal Pulsatile Blood Pump. The outflow of the pump is received by the compliance chamber. This device provides the volume expansion per increase in hydraulic pressure that simulates the elastic expansion of arterial tissue [1,2]. The outflow of the compliance chamber leads to the resistance device. This particular device employs a plunger based design that is actuated via a linear stepper motor assembly. Resistance is achieved by controlling the orifice size through which the system fluid passes, in order to reproduce the peripheral resistance of the circulatory system [3]. The outflow empties into an opened topped reservoir via an outlet above the fill line; this decouples the flow to prevent level changes in the reservoir from affecting the upstream conditions. The reservoir provides the feed capacity needed for the inlet flow rate necessitated by the pulsatile pump, and replicates the large blood volume present in the venous system. From this device, the pulsatile blood pump draws the system fluid it pumps to the rest of the system resulting in a closed loop circulation.

Arterial compliance provides the capacitance of the circulatory system, which is crucial in maintaining the blood pressure during ventricular diastole and dampening pressure waves. The use of compliance chambers for simulating the elastic effects of circulatory tissue provides an effective means of lumped parameter testing; the entirety of elastance in the system being simulated is represented in a singular device. Compliance values in the human population vary according to age, sex, and health [4,5]. Compliance chambers that are capable of simulating a range of settings provide an *in vitro* method for assessing a device's performance for a prescribed compliance value. Compliance has been found to change during pathological events as well, which is consistent with the biomechanics of the arterial tissues [2,4]. For a complete mock circulatory loop investigation of a device, it becomes necessary to simulate a range of compliance values and include the capability to change the compliance during pumping. This testing approach validates a range of a device's functionality in serving various demographics and assessing the device performance during critical events.

There are three main design types for compliance chambers in mock circulatory loops: membrane-based chambers [5], spring-based chambers [6], and pneumatic only chambers [7]. The first is the architecture chosen for this design due to the accuracy with which the membrane can be measured for volume expansion in the compliance calculation, and this structure's low hydraulic impedance. The spring-based designs are more complex in their hermetic seals, and are subject to higher impedance due to the seal friction. The use of a nonmembrane design provides an effective means of compliance, but poses the challenge of accurate liquid volume change measurement. Mass flow sensors must be used for the pneumatic system in order to use ideal gas laws for volume and pressure correlations. Ultrasonic liquid level sensors can be used, but are dependent on the system fluid physical properties and do not account for sloshing at the surface. The membrane design provides a geometrical constraint for accurate volume expansion determination, and is not dependent on system fluid physical properties.

With the utilization of advanced control systems, it becomes advantageous to construct fully automated mock circulatory loops that are capable of real-time changes in testing conditions. Automation allows for battery testing the multitude of circulatory conditions, the ability to simulate the changes in circulatory loads, and affect precise control over flow conditions in the simulation. In order to produce the physiologically accurate dynamics, it becomes necessary to employ real-time measurement and control of the mock circulatory loop parameters. The past control of pneumatic compliance chambers has involved stopping the circulation of the mock loop to change the header air pressure, or changing the air pressure during operation and inferring the compliance from pressure waveforms [5,8]. Development of a real-time control scheme that can accurately determine the instantaneous compliance and actuate control to a desired set point delivers a robust means of simulating arterial compliance in an automated system.

Manuscript received January 6, 2012; final manuscript received September 21, 2012; published online November 21, 2012. Assoc. Editor: Paul A. Iaizzo.

1.2 Membrane Elasticity. The mechanical behavior of the membrane at the interface of the hydraulic system and pneumatic system in this design is a classic deformable material problem. The expansion of a clamped circular plate with large deflections is a problem that has been analytically proven, which allows for an accurate numerical model to be developed in this application [9]. The plate in this application is 0.006" thick, has a radius of 2.375", and will have deflections up to 2.000"; thus, only membrane stresses should be considered in the problem statement [10]. The bending moment forces can be neglected due to the small cross-sectional area of the membrane, and the highly elastic properties of the natural latex rubber used in the design. The elastic nature of the material chosen for this design provides that even with the large deflections, the material should not undergo plastic deformation. The numerical model for this solution includes deflection in the longitudinal and radial directions due to the large deformations of the plate. Axial symmetry and the assumption of material continuity maintain that the circumferential deflections are zero.

The method used to develop the numerical model for this membrane was a strain energy equation [9]. A strain energy method defines a summated global potential energy (scalar) in a structure at particular deformations. A minimum in strain energy is reached at a steady state of loading from a force balance of the stress in the structure. This minimum is dependent on the material properties and geometry of the structure. The potential strain energy for a clamped circular membrane is defined by the following equation with the variable definitions in Table 1:

$$U_m = \frac{\pi E t}{1 - \gamma^2} \int_0^a \left[\left(\frac{du}{dr} \right)^2 + \frac{du}{dr} \left(\frac{dw}{dr} \right) + \frac{u^2}{r} + \frac{2\gamma u}{r} \frac{du}{dr} + \frac{\gamma u}{r} \left(\frac{dw}{dr} \right)^2 + \frac{1}{4} \left(\frac{dw}{dr} \right)^4 \right] r dr \quad (1)$$

The axial and radial displacements are, respectively, defined by the following two equations (see Table 1 for variable definitions):

$$w(r) = w_{\max} \left(1 - \frac{r^2}{a^2} \right)^2 \quad (2)$$

$$u(r) = r(a - r)(c_1 + c_2 r) \quad (3)$$

The coefficients of the radial displacement (c_1, c_2) are determined from a minimization of the potential strain energy equation for a particular radius of the circular plate and Poisson's ratio of the material. The Young's modulus is a global scalar to the potential energy minima, and has no regional effects in the strain field as it is not in the integral. If the $w_{\max}$ is known, the displacement profile of the membrane can be determined. From axial symmetry, the revolved profile can be integrated to determine a volume displacement of the circular plate. This provides the $w_{\max}$ to volume distention relationship needed to implement a $w_{\max}$ -to-volume

conversion method for use in the calculation of instantaneous system compliance.

1.3 Simulink Modeling With Simscape. The goal to develop an accurate computational model, shown in Fig. 3, was reached with the Simscape® (The MathWorks, Natick, MA) block set for Simulink™ (The MathWorks, Natick, MA). The Simscape blocks allow the modeling of physical systems with computational components based on physical parts used in these assemblies, with tunable parameters relating to values typically available in data sheets for these parts [11]. The blocks utilized in this computational model were taken from the hydraulics foundation library for Simscape®, the mechanical foundation library for Simscape®, and the SimHydraulics® (The MathWorks, Natick, MA) toolbox.

The advantage of this method is the specificity of the model elements to the physical components that are being modeled. This is a departure from previous methods, such as the use of electrical elements, to represent physical components in computational models [12,13]. The items that are available in the Simscape® toolboxes limit the number of assumptions needed for simpler modeling methods, and they supplant the need for the inordinate amount of programming otherwise required to achieve higher fidelity representation of complex elements. The establishment of a Simulink™ model furnishes the control designer with the availability of the numerous libraries associated with Simulink™ and MATLAB® (The MathWorks, Natick, MA).

If a device is custom, and lacks the data sheet reference for parameters required in the corresponding computational block, a Parameter Estimation™ task can be performed to identify possible values. This estimation involves an experimental dataset to tune the computational model parameters; minimal error between the model simulation and experimental data occurs with parameters that correctly describe the components of the model. This estimation process necessitates the use of Simulink™ Design Optimization™ (The MathWorks, Natick, MA), Simulink™ Control Design™ (The MathWorks, Natick, MA), Matlab Control System Toolbox™ (The MathWorks, Natick, MA) and Matlab® Optimization Toolbox™ (The MathWorks, Natick, MA). The physical configuration should reflect the Simulink™ model as closely as possible, especially with respect to sensor placement. The fidelity of the reflection of the physical system in the computational model correlates to the accuracy of the determined parameters.

2 Materials and Methods

2.1 Compliance Chamber Design. The compliance chamber is a cylindrical chamber with a hydraulic and a pneumatic compartment divided by a transverse circular membrane (Fig. 1). This design allows for forces to be transmitted through the membrane while maintaining separate liquid and air environments (Fig. 2). The only distensible boundary in the hydraulic system is at the membrane, which ensures the volumetric expansion in the entire mock circulatory loop occurs only at this surface and therefore allows the compliance in this chamber to be that of the entire mock circulatory loop. A laser displacement sensor monitors the center displacement of the membrane through a window into the pneumatic chamber. By controlling the expansion of the membrane from pressure developed in the hydraulic compartment, the compliance enacted by this device can be accurately controlled. The hydraulic compartment of the device has an inlet and an outlet radially oriented to produce a transverse flow path through the chamber. The inlet and outlet are 3/4" ID acrylic pipe conduits with sharp edged circular orifices into the hydraulic compartment. The inner diameter of the cylinder is 5.75" and the height from the base of the hydraulic compartment to the membrane is 2.75". The inlet and outlet conduit centerlines are 1.5" from the bottom of the compartment. This geometry allows for the incoming and exiting flow to have minimal effects from surrounding walls. A bleed port was installed near the membrane interface to allow for air to be released from this compartment when a membrane is

Table 1 Definitions of variables utilized in equations

Variable	Definition
U_m	Total membrane strain energy
E	Young's modulus of the membrane material
t	Thickness of the membrane
γ	Poisson's ratio
a	Radius of membrane
u	Radial displacement
r	Radius
w	Vertical displacement
$w_{\max}$	Largest vertical displacement
c_1	Coefficient for radial displacement
c_2	Coefficient for radial displacement

Fig. 1 One of the membrane cartridges developed for the compliance chamber. The latex sheet is adhered to acrylic rings and cut to size. These cartridges allow for ease of replacement in the membranes, tracking of membrane use to ensure they are replaced after appropriate durations of use and prevention of prestretch during installation into the compliance chamber.

installed. During installation, the membrane is pressurized such that it distends into the hydraulic compartment. This causes any air to aggregate at the edge of the chamber. The bleed valve is opened to allow the air to escape and is closed when the hydraulic chamber has been purged of air. The air chamber is bled to allow the membrane to revert to its operational state, distended into the air chamber.

The membrane is comprised of natural latex rubber with a thickness of 0.006" and a Young's modulus of 130 pounds per square inch (psi). This highly elastic material is ideal for this cyclic loading application, and will not have a large force contribution range of strain during use [14]. This lack of force development for the range of distention provides that the pneumatic control over the compliance will be more exacting without having to account for the membrane contributions. The latex material is adhered to an acrylic ring under a no load state, creating a cartridge to be inserted into the compliance chamber. These cartridges prevent the membrane from having to be stretched when installed and provide an efficient means of replacing membranes. The cylindrical housing of the hydraulic compartment has a pedestal cut on the inner surface that holds the rubber gaskets and membrane cartridge.

The pneumatic chamber is comprised of a cylinder that has been machined to insert into the hydraulic counterpart. The housing of the pneumatic chamber is compressed downward via spring loaded clamps on the side of the assembly. With the upper and lower gaskets on the membrane cartridge, both the hydraulic and pneumatic chambers are hermetically sealed. The pneumatic chamber has two ports on the cap to the cylinder; one interface to the pneumatic proportional valve controlling the pressure and another to a safety valve that is set to release at 7PSI to prevent overpressure. The measurement limit of the pressure sensors in the mock circulatory loop is 5PSI, which governs the safety pressure limit for the pneumatic system.

The laser displacement sensor is mounted on the cylinder cap, with a clear acrylic window to allow its monitoring of the membrane center displacement. The device chosen was a Micro-Epsilon (Raleigh, NC) OptoNCDT 1402-50. The displacement sensor has a range ± 60 micron measurement accuracy in a measurement range of 50–95 mm. This equates to a submilliliter accuracy determination in the volume distention of the membrane,

and is capable of 1.5 KHz sampling rates. Equations (1)–(3) provide the center deflection distance to volume relationship through revolute integration of the deformed profile. This relationship is verified periodically through a calibration of volume distention by closing the upstream and downstream hydraulic ball valves to the compliance chamber and injecting known volumes of system fluid into the chamber via the air bleed line (Fig. 2). This calibration accounts for any strain irregularities in the material that may have been present during the fabrication of the cartridges and provides a suitability check of the membrane to indicate if a replacement is needed (Fig. 1).

The pneumatic valve utilized in this design is a voice coil actuator (VCA) based LS-V15s (Enfield® Technologies, Trumbull, CT) 5/3 bidirectional proportional valve with a normally closed center. The valve is being driven by a LS-C27 (Enfield® Technologies, Trumbull, CT) pulse-width modulation based electronics board with an integrated closed loop current control. This pneumatic assembly is capable of 2.5 ms shifting time and high flow rate, which are both crucial to the response necessitated by this application. With the controller operating at 500 Hz, a fast valve response is necessary for acute control of the membrane deflection. The inlet has a source pressure of 25 PSI and the outlet is connected to atmosphere. Thus, the high flow rating would provide the flow capacity for the chamber's vent to atmosphere. Previous work with solenoid proportional valves did not provide the flow rate and fast response time at the low differential pressures existing in this system. Voice coil actuator based valves do not rely on the differential pressure across the valve spool to supplement the force needed for actuation, and can generate force rapidly. These characteristics provide VCA based valves with the fast switching times and pressure independent operation, which were both desirable in this application.

Fig. 2 The compliance chamber design illustrating the various components utilized: (1) pneumatic lines, respectively, connected to the pressure regulation block and the emergency pressure relief valve; (2) laser displacement sensor monitoring the membrane center deflection, (3) pneumatic pressure sensor, (4) air bleed line, (5) hydraulic pressure sensor, (6) hydraulic chamber, (7) membrane cartridge between two black O-rings, (8) air chamber, (9) clamps used to create a hermetic seal between the compartments, (10) and the mounting rail for the assembly. The arrow indicates the direction of flow through the chamber. Not shown are the pneumatic pressure regulation block and the amplifier boards for the pressure sensors.

Fig. 3 Simulink™ model of the compliance chamber indicating the three different domains the model is able to simulate. The hydraulic section is comprised of a flow rate source with pipe sections leading to and one exiting from the hydraulic chamber. The resistor creates the backpressure to the flow, with the 655 value indicating the stepper motor position needed for a 0.022 in² equivalent hydraulic orifice. The membrane section illustrates the interface of the mechanical element of the membrane, the pneumatic contribution from the air pressure above the membrane, and the hydraulic pressure acting on the membrane. The motion sensor in this section provides the analogous reading of membrane deflection that the laser displacement sensor is providing in the physical system. The pneumatic section simulates the pressure regulation system that drives the air space pressure changes. Controller calculations are conducted in blocks located in the upper right of the model, which are interfaced with sensors connected to the appropriate domains of the system.

Pressure sensors are mounted on the cylindrical wall of the hydraulic compartment and the top of the pneumatic compartment. The hydraulic compartment sensor is used for the control of the compliance, and is the measurement point for the fluid pressure used by the process controller. The pneumatic pressure sensor is used as a process monitoring point, and is not used in the control algorithm of the airspace pressure. The pressure transducer models utilized were Entran EPX-V01-5P's (Measurement Specialties Corporation, Hampton, VA), with amplification of these transducers achieved through custom amplification boards. Each sensor is calibrated at every system start to a PX202-15G5V (Omega Corporation, Stamford, CT) transducer being amplified by a DP25-S (Omega Corporation, Stamford, CT). The data acquisition of the pressure and displacement data was performed with a National Instruments™ Corporation (Austin, TX) PCI-6024E DAQ card, which is capable of 16-bit analog to digital (A/D) conversion and 200 KS/s. The sampling rate used to log the experimental data is 512 Hz. LABVIEW (National Instruments™ Corp., Austin, TX) was used to construct an interface to the compliance chamber controller and log the experimental data.

2.2 Simulink™ Physical Model. The Simulink™ model developed for this system illustrates the multiple domain elements that were used to produce a high fidelity simulation of the physical system. The pneumatic, hydraulic and mechanical sections contain elements that are generalized numerical models for that particular functional component in that domain. Sensor elements in the model replicate the sensor data being acquired in the physical system. The PI controller is shown in the model, with connections

from the sensors to the actuators. This computational model provides a robust design tool, which allows for controller parameters to be accurately determined in silico to reduce experimental tuning time.

The elements used in the hydraulic section were taken from the Simscape® Foundation Library and SimHydraulics® toolboxes. The hydraulic section of the model contains an inlet connection, a pipe conduit into the chamber, a hydromechanical converter, an outlet conduit, and the outlet connection. The hydromechanical converter element transmits the hydraulic force into a mechanical force which interacts with the membrane mechanical element and the pneumatic piston. The displacement of the mechanical section of the converter represents volumetric change in the fluid section. This element represents the hydraulic volume change in the space under the membrane, and the transmission of mechanical force at the membrane.

The mechanical elements were taken from the Simscape® Foundation Library toolbox. The membrane element is modeled by a linear spring. The highly elastic natural latex rubber produces minimal pressure development with distention, and this spring element would analogously have a low spring constant [9]. The spring strength is minimal, and the need for a nonlinear spring was not necessary in the range of use for this membrane. The force produced by this element represents the normal projection of force in the membrane due to the tension from expansion. The arrangement of the element in parallel with the pneumatic piston provides that the bulk of the force from the hydromechanical converter will be transmitted directly to the pneumatic section, with the membrane contributing only a slight mechanical response.

Fig. 4 A diagram of the run-time loops programmed for the compliance control, with functional connections to external components, is shown. A fast 500 Hz timed loop with a low priority interrupt is used to capture the sensor data. The displacement sensor is used to determine the current volume of the membrane. The fluid pressure is used in the computation of the volume set point. The air pressure is monitored to ensure operation within the safety limits. After the volume error is determined, the PI controller actuates the pneumatic system to maintain the compliance desired. The communication with the computer is a high priority interrupt that processes the set point changes and returns measurements to the data logging system.

Pneumatic elements were taken from the Simscape® Foundation Library toolbox. The pneumatic section consists of a piston that is able to produce mechanical force from pressurization of its air chamber. The piston is connected to the proportional valve elements via a pneumatic tube. The pneumatic manifold subsystem in Fig. 3 is comprised of the pneumatic valve model representing the 5/3 bidirectional proportional valve, the electronic valve driver board, the inlet pressure source of 15 PSI, and the outlet connection to atmosphere. Actuation of this valve is delivered by a control signal originating from the PI controller, which is converted into a scaled response signal through a lookup table. This table represents the orifice opening to control signal calibration curve: the analogous voltage level to percent opening in the physical system. The valve response time, denoted as a 2.5 ms shifting time in the datasheet, was modeled as a first order system in the pneumatic manifold subsystem (Fig. 3).

A displacement sensor on the membrane spring element is reflective of the measurement by the laser displacement sensor on the center displacement of the membrane. The output of this displacement sensor is passed through the volume determination block to provide the equivalent volume distention. A pressure sensor in the hydraulic chamber is routed through a compliance curve lookup table which denotes what the volume distention should be at that particular hydraulic pressure. This value is the set point for the controller, the calculated volume from the displacement sensor

value is the read back. The error is passed to a discrete PI controller block with a sample time of 0.002 sec, analogous to the 500 Hz process control loop on the microcontroller. The output of this controller is then actuated in the pneumatic manifold. Floating point calculations are not used on the hardware controlling the compliance chamber, which necessitates the use of specific data types in the computational model for fidelity purposes. The computational model enforces the bit precision utilized on the physical hardware in terms of analog to digital conversion (ADC), mathematical calculation rounding errors, and precision of the output controlling the pneumatic valve.

Mandatory blocks for the simulation of this system are presented in Fig. 3; the Solver Configuration block establishes the handle for the ODE solver and is required for every Simscape® system. The hydraulic fluid block contains the physical properties of the fluid being simulated; 40% glycerin in water at 22 °C. The membrane mass represents the small mass contribution (50 mg) of membrane to the mechanical system, and is necessary when using the mechanical block elements. The heat sink is required for the pneumatic piston, and allows for ideal gas laws to be maintained in the solution of the pneumatic equations. The gas law block contains the gas properties for the pneumatic section.

Pressure sensors for the hydraulic and pneumatic points of the system were included. These were used in the parameter estimation process to determine values of parameters utilized in the

Fig. 5 Experimental performance of the compliance chamber process controller. The pulsatile flow settings were 50 bpm, 30% systole and 80 ml stroke volume. The peripheral resistance was simulated to be equivalent to a 0.022 in² hydraulic orifice. The first plot includes the fluid pressures of the experimental and computational models. The middle plot contains the flowmeter data, which is interpreted as left ventricular output. The bottom plot indicates the curve slope used to control the compliance and the determined slope from regression analysis. The calculation of the compliance through linear regression of the pressure-volume curves is plotted against the setpoints to illustrate the performance of this controller. Large deviations at the transitions to new curve settings are seen, but are expected in this state of set point change.

blocks. The Parameter EstimationTM tools in SimulinkTM utilize cost function analysis to determine the accuracy of the model to that of experimental data. Descriptive experimental data from the physical system is required, with accurate depiction of sensor placement in the computational model [15]. Multiple sensor data provides a more efficient parameter estimation task, as the system is able to delineate the effects of parameter changes in particular elements more acutely.

2.3 Microcontroller Programming. A Microchip (Chandler, AZ) PIC18F26K22 microcontroller unit (MCU) was used as the platform for the process controller governing the compliance chamber function. This MCU was chosen due to its processing power of 20 mega instructions per second (MIPS) and features that would allow it to handle the peripheral devices involved in the compliance chamber control. The C18 student compiler was utilized in conjunction with the MPLAB[®] IDE (Microchip, Chandler, AZ) to produce the code deployed in this application. A PICkitTM 2 (Microchip, Chandler, AZ) was used to program the MCU with the compiled code developed in MPLAB[®]. The use of a distributed process control design allows the compliance chamber subsystem to remain stable in the event the host computer goes offline. The use of a MCU, as opposed to a programmable logic controller (PLC), was dictated by the relatively simple cal-

culations needed for this application and the cost differential between an MCU and PLC.

The run-time loop involves two main processes: timer interrupt at a frequency of 500 Hz and receive interrupt from the computer controlling the mock loop (Fig. 4). The timer interrupt loop is tasked with taking measurements from the pressure sensors and laser displacement sensor; this is a low priority interrupt. The hydraulic pressure value is used to determine the compliance chamber membrane volume set point, and the stored value of the current membrane volume is retrieved to provide the PI controller with an input error. The PI controller output is directed to a digital to analog (DAC) IC, which drives the proportional valve electronics. The receive interrupt from the computer is high priority, as these commands should execute immediately. The connection with the computer is used to change the set points on the MCU and take read backs for the purpose of data logging in the experiments.

3 Results and Discussions

3.1 Computational Model. The fidelity of the computational model to the physical compliance chamber behavior was found to be high. This accurate model allowed the discrete PI controller to be tuned appropriately, with computational simulation of its

Fig. 6 Pressure versus volume (PV) curves for the data presented in Fig. 5. The dashed lines indicate the set point curves used to control the compliance. The black curves are the plots of the experimental PV. The light gray line segments represent the regression performed on the systolic and diastolic sections of the experimental PV curves. The numbers at the top of each set point curve indicate the slope of that setting. The black traces between the curves result from the controller's migrating to a new curve. Congruency of the set point, experimental and regression plots illustrate this control method's ability to accurately execute control of the system compliance using a curve-based set point method.

performance indicating an effective control of the membrane distention through manipulation of the air pressure. Plotting the experimental and computational pressure data in the top graph of Fig. 5 illustrates the fidelity of the computational model with the overlapping hydraulic pressure data. Initial conditions of the computational model prescribe a depressurized and stationary system; the experimental system as depicted in Fig. 5 has been operating prior to zero seconds. This accounts for the discrepancy seen between the two simulation modalities in the first ten seconds of Fig. 5. Nonetheless, the computational model effectively simulates the pressure response to compliance set point transitions and maintains an accurate representation of the physical systems performance.

The successful construction of the computational model was based in the parameter estimation of component values and the PI controller tuning. The estimation of the spring constant for the element modeling the membrane equivalent piston force contribution was found to be 0.01 lbf/in. This is consistent the pressure produced by a circular membrane with a low elastic modulus [9]. The pneumatic valve controller dead space was determined via parameter estimation, and was found to be in the control signal region of 2325 mV to 2490 mV. The PI controller values resulting from the tuning were -200.5 for the proportional gain and -24.8 for the integrator gain, in a parallel design [16]. A clamping method was found to be the best means of antiwindup for the integrator. The results of the parameter estimation and controller tuning aided in the construction of the high fidelity model and precise controller design, respectively.

The computational model was an excellent development tool with respect to system component selection and diagnosing experimental performance issues. The pneumatic valve selection was a direct consequence of diagnosing the inability of the solenoid based valves to perform in this system. The fidelity of the model allows for parameters of the computational network to be measured easily during the design phase. In the case of the valve selection, the flow rate could easily be determined in the computational

model and identified as a crucial parameter in the selection of an appropriate valve. The computational model was important in determining the minimum controller update frequency, and gain values, for the range of cardiac conditions to be simulated. The final compliance chamber performance benefited directly from the in silica design testing achieved with this computational model.

3.2 Compliance Chamber Performance. The numerical model provided a precise PI controller design that proved successful at regulating the compliance in the model. The experimental results echoed this success, and showed the same level of performance. The physical model implementation of the controller design exhibited the same characteristics of fast set point rise time and disturbance rejection in maintaining the set point. The response time in the physical model is a not as rapid as in the computational model, but the performance still positions this design as a success.

The results of the controller performance are shown in Fig. 5 through the implementation of a staircase compliance curve set point change. Compliance curves with slopes ranging from 0.8 mL/mmHg to 2.0 mL/mmHg in 0.4 mL/mmHg steps were executed, all with an intercept of 100 mL. Regressions of the pressure-volume curve were taken for the systolic and diastolic time segments. These regressions provide the analysis of the controller's ability to maintain the curve dictated by the set points. The slopes, which are the compliance, from the regression analysis are plotted against the set points in Fig. 5. Error bars were

Fig. 7 Screenshot of the LABVIEW control panel for the compliance chamber during an experiment. The compliance graph presents the current volume-pressure value present in the chamber (white) with the set point curve overlaid (gray). The dial gauge indicates the valve opening in percentage; negative indicates venting and positive corresponds to positive pressure opening. A switch to activate or deactivate the controller is included for safety in the case of instability, or for investigations without compliance control. The led indicates that the controller is appropriately enabled or disabled. The reset graph button clears the compliance graph at the top, which is useful when a new compliance curve is actuated. The inputs in the lower right are for the compliance curve of interest; slope and intercept pertain to the volume-pressure curve that is to be followed by the controller. The ability to set and read the integrator value is useful in expediting controller response and monitoring controller performance, respectively. The update settings button communicates to the MCU the controller state and the curve values to be used.

included to illustrate the precision of the controller in maintaining that compliance. The outliers of seen in the regression analysis occur at set point changes, which were anticipated. The capability of the system to migrate to a new compliance in the duration of one heartbeat was seen as acceptable. This performance is reflected in bottom plot of Fig. 5, where the regression results quickly assimilate to the set point after one transition beat. It was found that the controller was able to maintain a set point curve slope appropriately, and rapidly adapt to set point changes.

The pressure volume curves for the data presented in Fig. 5 are shown in Fig. 6 with overlays of the set point curves and the results of the regression analysis. This provides a clear representation of this control method's ability to effect system compliance changes and maintain a compliance curve during pulsatile flow. After the initial set point change, the system will operate on the new curve away from its steady state region. The assimilation of the system to the steady state operating point for the new compliance is dependent on the pumping rate of the system, the peripheral resistance being simulated, and the compliance curve slope. The operating region for the volume distention has been determined to lie in the region of 50 to 250 mmHg and 50 to 300 mL. This region provides the appropriate driving pressure in the hydraulic region for volumetric expansion. The volume constraints maintain the shape of the membrane at the lower bound and a buffer region at the end of detection for the displacement sensor. Maintaining the system operation within this region provides the stability and control capability evident in the presented results.

3.3 Software Interface. The LABVIEW interface developed for this application presents a user-friendly interface to the functionality delivered by this control design (Fig. 7). The control panel for the compliance chamber includes a compliance curve read back panel that graphs the current volume of the membrane to the hydraulic pressure in the system, with an overlay of the set point curve currently in effect. A reset button allows the graph to be cleared when a new compliance curve is selected. Inclusion of read backs on the valve activity is presented in a dial gauge for reference, and detection of a failure in the controller. A process controller activation switch is included to provide a safety cutoff in the event that the controller becomes unstable. Inputs for the curve slope and intercept offer the option to change the compliance in real-time. The controller's integrator value is able to be set to a particular value, and is set to zero on the execution of a new curve to reduce the rise to set point time. The read back on the integrator value is available as a diagnostic tool for monitoring controller performance. The maximum update rate afforded by the script is 8 Hz. This is also the rate at which the read backs on the valve activity and controller state are returned.

4 Conclusions

Real-time compliance control through the use of the direct volume measurement method on the membrane, coupled with a process controller capable of effecting control of the volume

distention, allows for a robust method of simulating arterial compliance in a mock circulatory loop. This method lends itself to the fully automated perspective being developed for the mock circulatory loop this assembly is integrated with. It also removes the dependence of inferring compliance from initial pressure-volume measurements or translating pressure waveforms to estimate compliance changes actuated. The accuracy inherent in this design will expand the investigational capacity of the mock circulatory loop to include simulations of nonlinear compliance and the effects relating to real-time compliance changes. This compliance chamber positions itself as not only a precise experimental tool, but one with a high fidelity computational model. The implementation of the SimulinkTM tools and the use of a MCU as the process controller deliver a development platform capable of rapid design deployment and scalability. The development methodology employed in the deployment of this device is certainly a strategy that will be implemented as a time saving workflow on other projects pertaining to this mock circulatory loop.

References

- [1] Fung, Y. C., 1997, *Biomechanics: Circulation*, 2nd ed., Springer-Verlag, New York.
- [2] Fung, Y. C., 1993, *Biomechanics: Mechanical Properties of Living Tissues*, 2nd ed., Springer-Verlag, New York.
- [3] Liptak, B. G., 2005, *Instrument Engineer's Handbook*, CRC, Boca Raton, FL, pp. 559–566.
- [4] Li, J. K. J., and Zhu, Y., 1994, "Arterial Compliance and Its Pressure Dependence in Hypertension and Vasodilation," *Angiology*, **45**(2), pp. 113–117.
- [5] Gregory, S. D., 2009, "Simulation and Development of a Mock Circulation Loop With Variable Compliance," M.S. thesis, Queensland University of Technology, Brisbane, Australia.
- [6] Woodruff, S. J., Sharp, M. K., and Pantalos, G. M., 1997, "Compact Compliance Chamber Design for the Study of Cardiac Performance in Microgravity," *ASAIO J.*, **43**(4), p. 316.
- [7] Liu, Y., Allaire, P., Wood, H., and Olsen, D., 2005, "Design and Initial Testing of a Mock Human Circulatory Loop for Left Ventricular Assist Device Performance Testing," *Artif. Organs*, **29**(4), pp. 341–345.
- [8] Papaioannou, T. G., Mathioulakis, D. S., Nana, S. J. N., Tsangaris, S. G., Stamatelopoulos, S. F., and Mouloupoulos, S. D., 2002, "Arterial Compliance is a Main Variable Determining the Effectiveness of Intra-Aortic Balloon Counterpulsation: Quantitative Data From an *In Vitro* Study," *Med. Eng. Phys.*, **24**(4), pp. 279–284.
- [9] Ugural, A., 1999, *Stresses in Plates and Shells*, WCB/McGraw-Hill, Boston.
- [10] Reddy, J., 1999, *Theory and Analysis of Elastic Plates*, Taylor & Francis, London.
- [11] The MathWorks, 2010, *Simscape 3.0 User's Guide*, The MathWorks, Natick, MA.
- [12] Yu, Y. C., and Gopalakrishnan, S., 2009, "Elastance Control of a Mock Circulatory System for Ventricular Assist Device Test," Proceedings of the American Control Conference (ACC'09), St. Louis, MO, June 10–12, pp. 1009–1014.
- [13] Liu, Y., Allaire, P., Wu, Y., Wood, H., and Olsen, D., 2006, "Construction of an Artificial Heart Pump Performance Test System," *Cardiovasc. Eng.*, **6**(4), pp. 151–158.
- [14] Komaragiri, U., Begley, M. R., and Simmonds, J. G., 2005, "The Mechanical Response of Freestanding Circular Elastic Films Under Point and Pressure Loads," *ASME J. Appl. Mech.*, **72**(2), pp. 203–212.
- [15] Miller, S., 2009, "Modeling Physical Systems as Physical Networks With the Simscape Language," 6th Vienna International Conference on Mathematical Modelling (MATHMOD 2009), Vienna, Austria, February 11–13.
- [16] The MathWorks, 2010, *Simulink 7.0 User's Guide*, The MathWorks, Natick, MA.