

Supersonic Blowdown Wind Tunnel Control Using LabVIEW™

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A computer-based, proportional-integral control system for supersonic blowdown wind tunnels was developed in a LabVIEW environment. The control algorithm is based on numerically integrating the differential equations used to model a supersonic blowdown wind tunnel in which the proportional and integral control terms were added and tuned in a simulation to determine their appropriate values. Values for these control terms can be obtained using a spreadsheet allowing for variation of the test section Mach number, test section area, stagnation pressure and plenum chamber volume as well as the pressure, temperature and volume of the storage tank. Accounting for the variation of many terms allows the control terms and resulting LabVIEW program to be easily integrated across different facilities. Experimental verification is provided along with a discussion of control valve calibration, optimization of control constants and additional capabilities of LabVIEW.

Nomenclature

A	=	test section area
A^*	=	nozzle throat area
C_l	=	control valve recovery coefficient
C_G	=	control valve gas sizing coefficient
c_V	=	specific heat at constant volume
c_P	=	specific heat at constant pressure
E	=	error
G	=	specific gravity (air = 1)
K_I	=	integral control constant
K_P	=	proportional control constant
M_D	=	desired test section Mach number
M_S	=	test section Mach number
\dot{m}_V	=	valve mass flow rate
\dot{m}^*	=	test section nozzle throat mass flow rate
N	=	samples per second
P_D	=	desired plenum chamber stagnation pressure
P_P	=	plenum chamber stagnation pressure

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P_S	=	test section static pressure
P_T	=	storage tank stagnation pressure
Q_{SCFH}	=	volumetric flow rate at standard conditions
R	=	gas constant
t	=	time
T_P	=	plenum chamber temperature
T_T	=	storage tank temperature
V_P	=	plenum chamber volume
V_T	=	storage tank volume
γ	=	ratio of specific heats
ρ_P	=	plenum chamber density
ρ_T	=	storage tank density
η	=	valve loss coefficient
θ	=	control valve angle (0° closed, 90° open)

I. Introduction

BLOWDOWN supersonic wind tunnels deliver flow at constant stagnation pressure.¹ The stagnation pressure is generally regarded to be equal to the plenum pressure which is controlled by one or more pressure regulators in a separate tank upstream of the test section. During a run, the storage tank pressure that supplies plenum chamber pressure decreases continuously. Thus, to maintain a constant plenum chamber pressure, the regulator valve must open progressively. In the facility at UT Arlington, the entire process is completed within 15–100 seconds. The method for controlling the valve opening to maintain a constant plenum chamber for supersonic flow facilities has evolved from manual operation to highly sophisticated neural net controllers²⁻⁵ that can maintain it constant during a run to better than 0.1 percent error. Pre-programmed controllers⁶ demonstrate good accuracy, but it may take several blowdown attempts before such a controller can be calibrated for a new test section Mach number or storage tank pressure. The controllers for tunnels that can operate at different stagnation pressures and Mach numbers must moreover be robust to accommodate the varying pressure and mass flow requirements safely. A dangerous situation known as “organ piping” can occur if the control system fails due to faulty adjustment of the control parameters. PI controllers are significantly less complex to operate than neural net controllers, but they are susceptible to organ piping unless correct control constants can be predicted. (Even for neural net controllers, the possibility of organ piping exists during the training stage.)

A control algorithm has been developed in the LabVIEW environment and uses the principles of a proportional-integral (PI) controller. The PI control method is widely used for single input, single output control systems. A block diagram describing the PI controller for the operation of a blowdown wind tunnel is shown in Fig. 1. Here, P_D is the setpoint plenum chamber pressure. The real-time error between P_D and $P_P(t)$ is then used by the LabVIEW PI controller to output $\theta(t)$, the control valve opening angle.

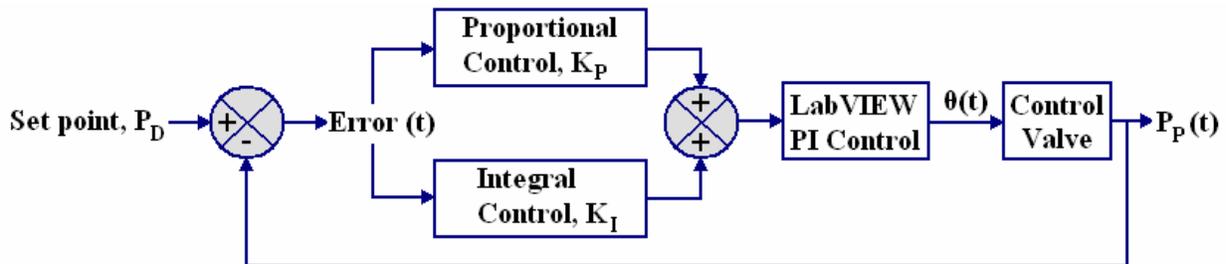


Figure 1. Block diagram of the PI controller implemented in LabVIEW.

Figure 2 shows a schematic of a typical supersonic blowdown wind tunnel with all of the variables needed for determining the PI control constants. The wind tunnel facility consists of a storage tank which holds the high pressure air, a plenum chamber which holds a constant stagnation pressure immediately downstream of the control valve, the test section and finally the diffuser. In the figure, the volumes V_P and V_T are based on the facility configuration and are constants. Other facility constants are the test section area A and the desired test section Mach number M_D . The plenum chamber setpoint pressure P_D must be specified by the user in LabVIEW. Real-time measurements of P_T and P_P are critical to the operation of the control program. T_T and T_P can also be measured in

real-time, but these parameters are less important than the pressures since they are both nearly equal to the initial value of T_T during the first few seconds of an experiment (where the response of the control program is most important). Real-time values of θ must be acquired in LabVIEW from the control valve with a new value passed to it during each time step of the program. Additionally, the control valve coefficients C_G and C_I are functions of θ . These values should be provided by the valve manufacturer and are used in the calculation of the valve mass flow rate. The test section static pressure should be acquired by LabVIEW to confirm the successful operation of the wind tunnel by calculating M_S from P_S and P_P by the isentropic formula.

$$M_S = \sqrt{\frac{2}{\gamma-1} \left[\left(\frac{P_P}{P_S} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]} \quad (1)$$

A successful control strategy will minimize the error in the P_P while actuating quickly enough to effectively use a limited supply of compressed air.

The PI control method developed is distinctive because suitable values for the control constants are determined by manually tuning them in a simulation which numerically integrates a set of differential equations for a typical blowdown wind tunnel and outputs a value for $\Delta\theta$ during each iteration. This method allows the user to observe the change in the controller performance for changes in the control constants K_P and K_I . Once suitable PI control parameters are determined, they are then entered into the LabVIEW program with the pressures, temperatures, and valve opening angle now being read in real time from the wind tunnel hardware instead of the simulated information. The LabVIEW and simulation programs both operate with a user determined frequency. With some experience, it becomes clear how to tune the control constants for adequate control over a wide range of test section Mach numbers. Thus, the LabVIEW PI control program is designed to have maximum flexibility should the wind tunnel configuration change, e.g., if the storage volume, test section pressure or test section Mach number changes. Additionally, this control scheme makes the process of changing test conditions between runs as desired by re-calculating the control coefficients faster than the time it takes to recharge the storage tanks.

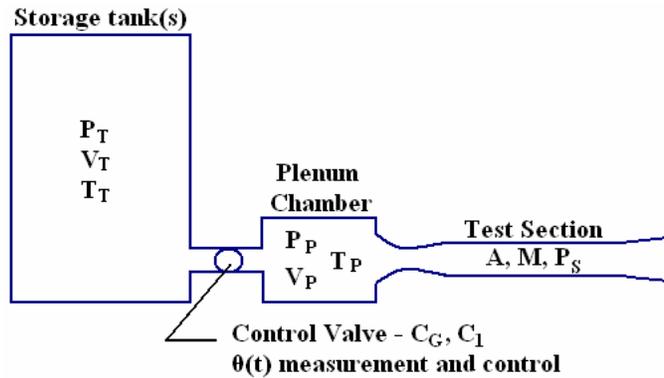


Figure 2. Schematic of typical blowdown wind tunnel.

II. Mathematical Model and Calculation of the PI Control Constants

Using Laplace notation, the transfer function of a PI controller can be written as⁷

$$G(s) = \frac{\Theta(s)}{E(s)} = K_P + \frac{K_I}{s} \quad (2)$$

Here, $E(s)$ stands for the error between the setpoint and its real-time value and can be rewritten as $P_D - P_P(s)$. Therefore, $\Theta(s)$ can be written as a function of K_P , K_I , P_D and P_P :

$$\Theta(s) = \left(K_P + \frac{K_I}{s} \right) [P_D - P_P(s)] \quad (3)$$

Applying an inverse Laplace transform to Eq. (3) results in

$$\frac{d\theta(t)}{dt} = -K_p \frac{dP_p(t)}{dt} + \frac{K_p}{K_I} [P_D - P_p(t)]. \quad (4)$$

Equation (4) is important to the development of the control scheme because it relates the PI control constants to $dP_p(t)/dt$ and $P_p(t)$, which can be determined by numerical integration. The numerical integration starts with the following initial values at $t = 0$ s: P_D , T_T , K_p , K_I , V_p , A^* (calculated as a function of A and M_D), V_T , P_T , P_p , T_p , and θ (starting at 0°). With these values initialized, the first step of the simulation is calculating the mass flow rate through the control valve, \dot{m}_v . This parameter is determined using the universal gas sizing relation, shown in Eq. (5a), which appears in industry labeled as Q_{SCFH} (standard cubic feet of air per hour) using BE units. Equation (5b) shows the universal gas sizing equation in SI units where \dot{m}_v is in units of kg/s.

$$Q_{SCFH} = \sqrt{\frac{520}{GT}} C_G P_T \sin \left[\left(\frac{3417}{C_1} \right) \sqrt{\frac{P_T - P_p}{P_T}} \right]_{DEG} \quad (5a)$$

$$\dot{m}_v = \frac{2.376 \times 10^{-6}}{\sqrt{T_T}} C_G P_T \sin \left[\left(\frac{3417}{C_1} \right) \sqrt{\frac{P_T - P_p}{P_T}} \right]_{DEG} \quad (5b)$$

The universal gas sizing equation accounts for the differences in the inlet and outlet geometry of a typical valve. The equation is a function of two pressures, a temperature, and two coefficients specifically related to an individual valve. Both coefficients C_I (valve recovery coefficient) and C_G (sizing coefficient) are functions of θ and should be provided by the manufacturer of the control valve. For the numerical integration, a least-squares, cubic equation was fit to the manufacturer's data.

Next, by means of the conservation of energy equation,⁸ the change in P_T over each time step $\Delta t = 1/N$ is determined:

$$\frac{\Delta P_T}{\Delta t} \approx \frac{-\gamma R \dot{m}_v T_T}{N V_T} \eta \quad (6)$$

In Eq. (6), η is the valve loss coefficient and accounts for the pressure losses through to the plenum chamber. The value of this loss coefficient can have a significant impact on the simulated experimental run times. The change in P_T in Eq. (6) is then used to calculate a new value of P_T over the time step.

$$P_{T,i+1} = P_{T,i} + \frac{\Delta P_T}{\Delta t} \quad (7)$$

Continuing in similar fashion, the nozzle mass flow rate⁹ is determined and used again with a derivation of the energy equation to find $\Delta P_p/\Delta t$.

$$\dot{m}^* = \left(\frac{2}{\gamma + 1} \right)^{\left(\frac{\gamma + 1}{2(\gamma - 1)} \right)} \sqrt{\frac{\gamma}{RT_p}} A^* P_p \quad (8)$$

$$\frac{\Delta P_p}{\Delta t} \approx \frac{\gamma R}{V_p N} (\dot{m}_v T_T - \dot{m}^* T_p) \quad (9)$$

$$P_{p,i+1} = P_{p,i} + \frac{\Delta P_p}{\Delta t} \quad (10)$$

Finally, Eq. (4) is rewritten to determine the change in the valve angle for each time step:

$$\Delta\theta = -K_p \frac{\Delta P_p}{\Delta t} + \frac{K_p}{K_I N} (P_D - P_{P,i+1}) \quad (11)$$

For each time step, the output $\Delta\theta$ is added to the updated value of $\theta(t)$. When $\theta(t)$ changes, the valve mass flow rate is affected and the program can iterate through a simulated blowdown run. The results can diverge with low initial values of P_T and P_D , but assuming an average value of C_I in Eq. (5b) will lead back to convergence. Figure 3 shows the simulated operation of the UT Arlington supersonic wind tunnel for $M_D = 2.5$ with $K_p = 0.00014$, $K_I = 0.2$, $P_T = 5$ MPa, $P_D = 700$ kPa and $N = 100$. The figure shows a linear decrease in storage pressure. To maintain a constant stagnation pressure, the valve opens up at a faster rate and becomes fully open at 42 s. The figure shows that the stagnation pressure drops at the same rate as the drop in tank pressure when this happens.

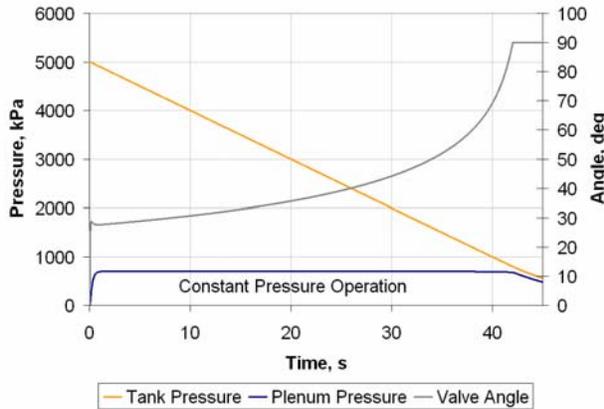


Figure 3. Simulated tank pressure, plenum pressure and valve angle versus time with $K_I = .2$.

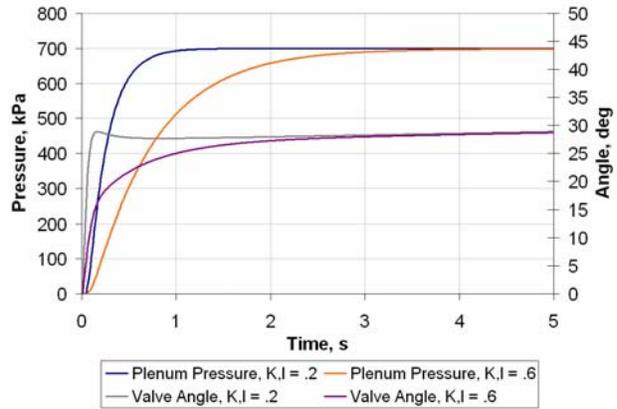


Figure 4. Plenum pressure and valve angle versus time with the K_I constant varied.

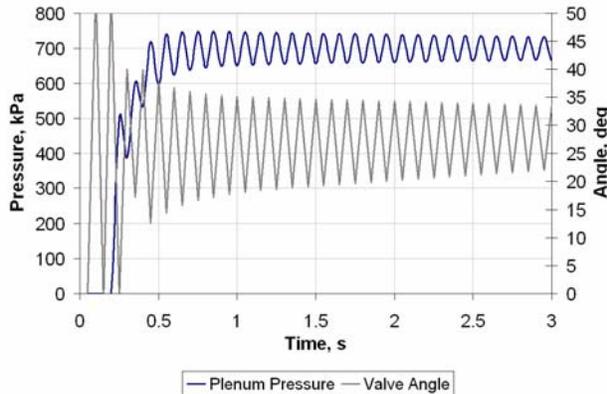


Figure 5. Selection of poor control constants leads to severe simulation oscillations and organ piping in actual wind tunnel runs.

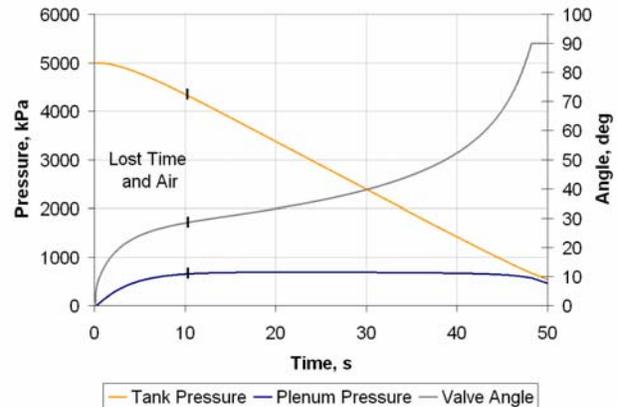


Figure 6. K_I is increased to produce a slow rise time resulting in a 25% head loss before reaching the plenum chamber pressure set point.

Figure 4 shows the first few seconds of the same simulation only using values of .2 and .6 for K_I . While manipulating K_p and K_I , it is obvious that a sizable range of values will work for a given set of initial conditions. However, there are two issues seen in actual blowdown runs that are not accounted for in the simulation. The first of these is the finite-rate filling time of the plenum chamber. Even for several megapascals of storage tank pressure, the plenum chamber pressure will not see an appreciable rise for the first half-second to second of operation. Two to three seconds of rise time has been demonstrated for these initial conditions,⁶ so using a value of .6 for K_I is more reasonable in this simulation. The second issue is the rate at which the pneumatically or hydraulically driven control valve can move. In Fig. 4, it is assumed that the control valve will be able to actuate to 30° in a tenth of a second for

the $K_I = .2$ condition. This is an extremely high travel rate for most control valves since industrial processes requiring them are relatively slow when compared to the needs of blowdown wind tunnels.

Figure 5 shows some results from selecting poor control constants in the simulation. Setting K_I to a low value resulted in the valve opening rapidly. This indicates that the control constants have generated a control signal that is too fast for the valve to catch up to. Although the signal reaches a steady oscillating state in the figure, the result in an actual run would be organ piping.

Figure 6 shows the results of using a large K_I value, which produces a slow and steady increase in plenum chamber pressure until the setpoint is reached. This result may be acceptable for facilities with large storage capacities, but here it wastes 25 percent of the head pressure before reaching the setpoint. Therefore, the selection of control constants for facilities desiring to conserve air is a balance between a rapid rise to the plenum chamber pressure setpoint which risks organ piping and a slower, steady rise which will result in a lower run time.

III. LabVIEW Program Design

Following the simulation, the LabVIEW controller was built around Eq. (11). The LabVIEW program is capable of passing values from one loop iteration to the next, allowing for the calculation of the plenum chamber pressure derivative. The user inputs needed for the program are K_P , K_I , P_D , T_T and the frequency (denoted as N samples per second). The storage tank temperature is considered a constant during a blowdown run since it does not change enough to cause a significant impact on the controller performance. This temperature is set as the ambient temperature of the outdoor storage tanks.

A. LabVIEW Program Development and Structure

The LabVIEW control program has been constructed based on the simulation, but with real-time thermocouple, pressure transducer and valve opening angle measurements being read into the program through a data acquisition system (DAQ). The program begins by reading in a plenum chamber pressure and an initial $\theta(t)_i = 0$ value. Next, it calculates $\Delta\theta$ which is added to form a new output valve angle, $\theta(t)_{i+1}$. Figure 7 shows the basic structure of the program. The pressure and temperature measurements are all calibrated before being passed to a series of equations which calculate $\theta(t)_{i+1}$ and provide safety during the blowdown run. The built-in program safety consists of a maximum and minimum user-specified plenum chamber pressure. If the plenum chamber pressure reaches the maximum allowable value, the control valve will immediately shut. This is especially important for the UT Arlington facility which has a maximum storage tank pressure of 5 MPa but a plenum chamber rupture valve currently rated to 1.6 MPa. Once the setpoint pressure is reached, the program will execute until the pressure drops to the minimum value and causes the control valve to shut (which conserves air).

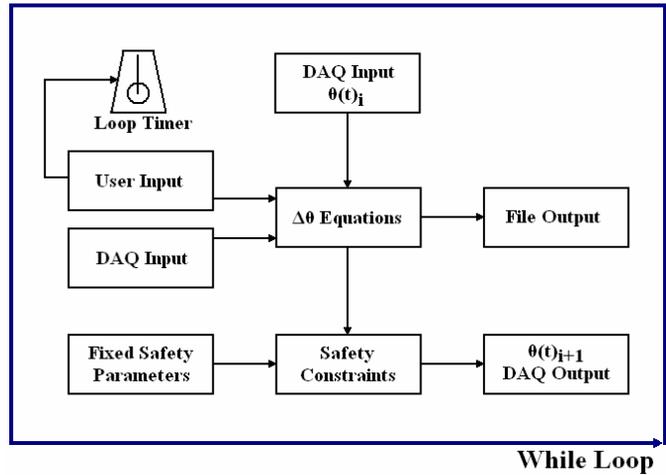


Figure 7. LabVIEW controller basic structure.

The entire program is contained in a WHILE loop which executes at the frequency specified by the user until the user stops the program. This is achieved by first setting the sampling rates of the DAQ inputs to an arbitrarily high value. Next, a feasible value of N can be wired to a loop timer so the time steps between LabVIEW and a given simulation are equal. Along with thermocouple measurements from the plenum chamber, all of the blowdown information is saved to an Excel file which can be used to calculate the Reynolds number of a run. The $\theta(t)_{i+1}$ output leaves the computer as an analog 0–10 V signal which is then converted into a 4–20 mA current signal which in turn linearly corresponds to a 0–90° actuation of the control valve. The control valve is fully open at 90°. It is possible for LabVIEW to output current signals, but most of the DAQ systems only support voltage outputs. A Fisher-Rosemount DPR-950 Digital Valve Controller has been modified to create the current, but this conversion can be achieved in many ways.

The elapsed time and several real-time properties are shown on the LabVIEW interface which gives the user the ability to see if the controller is working properly during a blowdown.

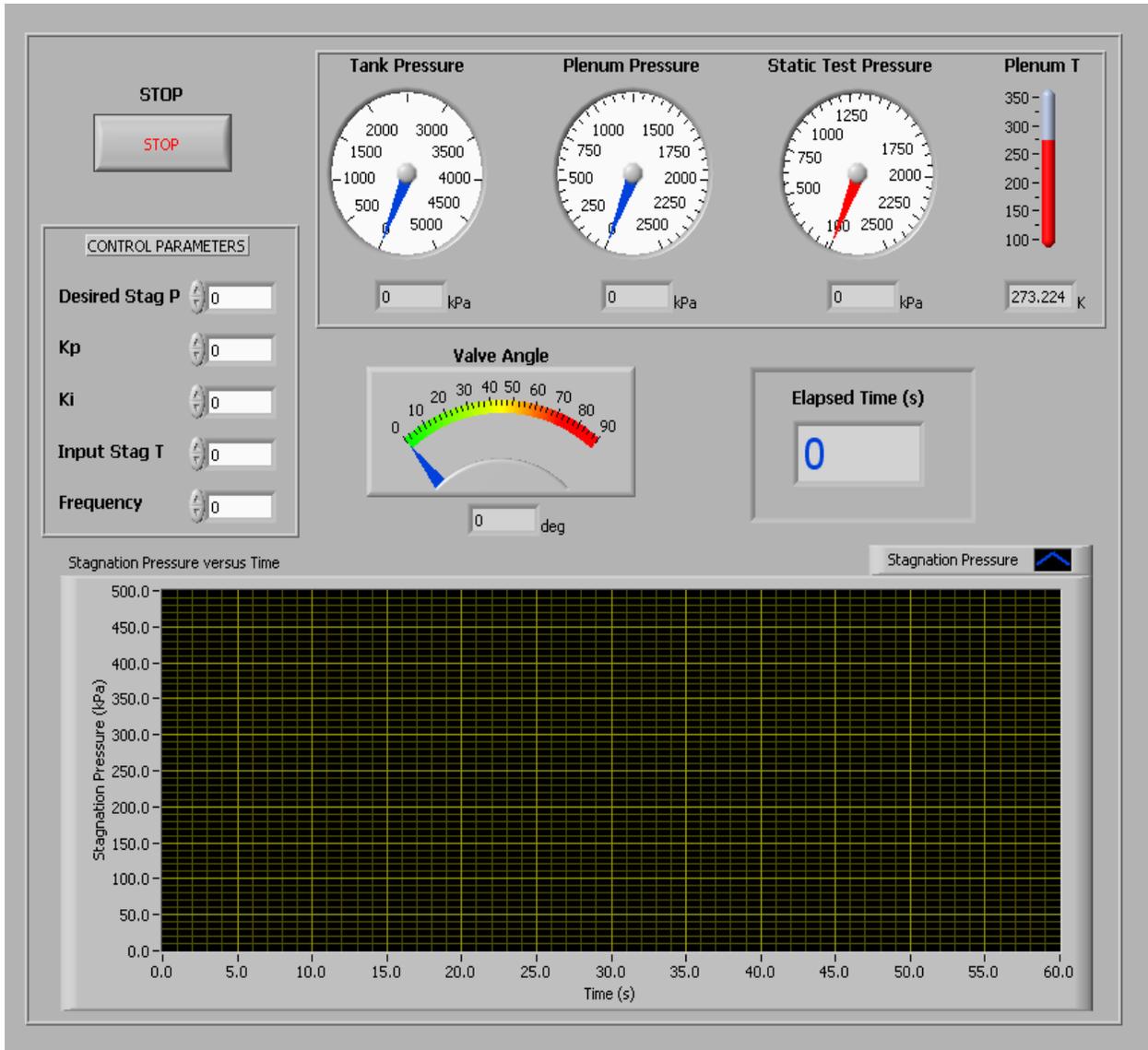


Figure 8. LabVIEW controller user interface.

B. Control Routine for Test Section Mach number Variation

In the past, the UT Arlington supersonic controller was preprogrammed⁶ to a specific Mach number of 2.5 and much effort was needed to change it as many runs are needed for the program to converge on a steady setpoint pressure for different run conditions. Therefore, the focus of the current program is for any variable-throat, supersonic blowdown wind tunnel to have the ability to change the desired test section Mach number and prepare to run before the storage tanks are refilled. In order to run an experiment, the user should first select a desired test section Mach number, set the variable-throat nozzle to the correct geometry and calculate the plenum chamber pressure required to sustain such a Mach number in the test section. Next, those choices together with the wind tunnel properties and ambient conditions are placed into the simulation program to determine K_p and K_i . After the control constants are determined, the blowdown can be executed. This process can be repeated while the storage tanks are being recharged, which takes 30 minutes at the UT Arlington facility. While it may be necessary take a few runs to optimize the control constants, constant plenum chamber pressure with an acceptable level of error should be attained during the first run if the simulation program has been run correctly.

The Mach number of the test section can be varied from 1.5 to 4 by changing the geometry of a variable throat nozzle. The nozzle area is adjusted by means of a geared mechanism driven by a 24 VDC, 1 h.p. bidirectional motor. A circular plate with angle markings from 0 to 360° rotates with one of the gears. The nozzle was donated by the LTV Corporation with a chart that matches the angle markings with test section Mach numbers. However, this motor was disabled and has been in disuse for a number of years. Without the motor, changing the nozzle geometry required manual adjustment of the gears before each run. The motor circuitry consists of two 24 VDC contactors and limit switches that were attached to terminals on the motor allowing it to run in forward and reverse to open and close the nozzle. These were controlled by two toggle switches, one for power and one for the forward and reverse motion. To automate the nozzle control process, the motor system was reconstructed with the intention of operating it using LabVIEW. Controlling a motor with a high current draw using LabVIEW presents several problems. First, the high power electrical circuitry of the motor cannot be directly driven by the small electronic circuitry of the DAQ system. Next, the DAQ system's output channels are limited in number so using three channels for turning on the motor and running in each direction was not desirable. Finally, no mechanism was in place to sense and feedback to the controller the position of the nozzle as the motor is operated. Normally a digital control system is used to interface the motor with the computer based setup. Since LabVIEW can output analog control signals, a simple circuit using inexpensive components was built to make the analog signal mimic a digital outcome. The interface circuit consists of op-amp based comparators and Darlington transistors to drive low power 24 VDC SPDT relays which in turn drive the larger motor contactors. Hence, a LabVIEW compliant logical algorithm was devised to output a steady DC voltage level for each motor state of off, on clockwise and on counterclockwise.

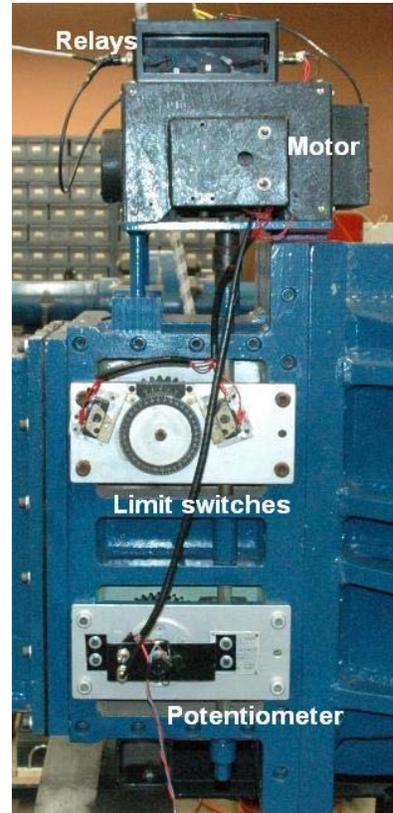


Figure 9. Nozzle motor control system.

The problem of sensing the nozzle position was solved by mounting a potentiometer on one of the rotating gears with the help of a bracket as shown in Fig. 9. The potentiometer is powered by a dedicated power supply and it generates a voltage signal proportional to the nozzle position. Driving the motor using LabVIEW has been achieved by passing the DAQ system voltage output to comparators which

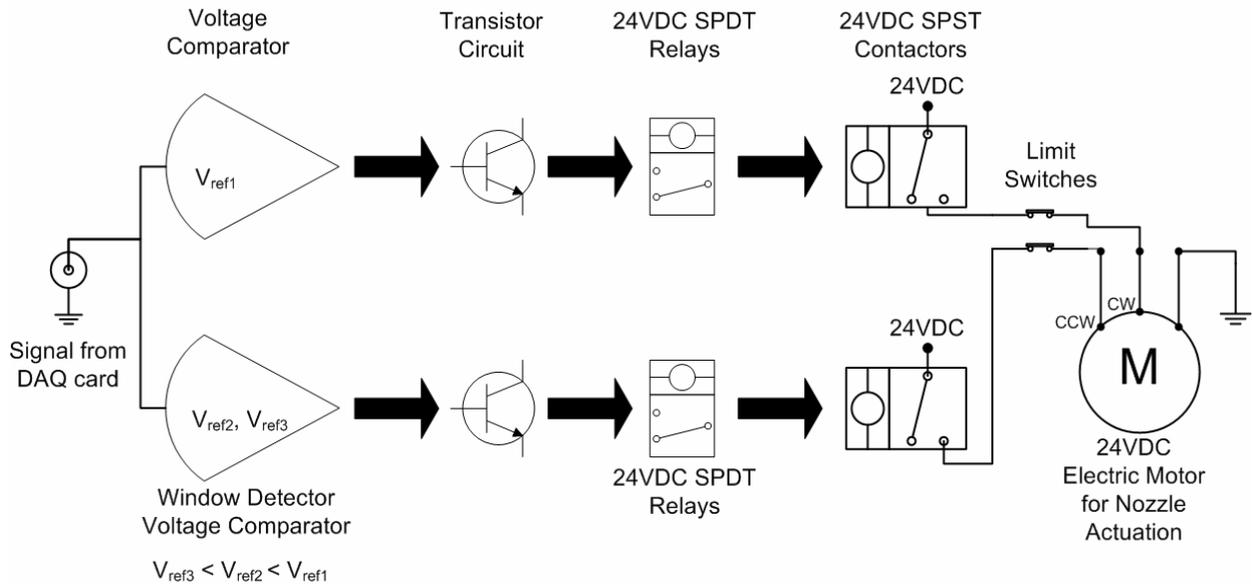


Figure 10. LabVIEW supersonic wind tunnel nozzle motor control system schematic.

activate separate sets of low power relays corresponding to the motor direction. Fixed reference voltages are used for the comparator which allows LabVIEW to run the motor clockwise with one voltage value and counterclockwise with another. Darlingtons transistors were incorporated to minimize the computer power requirement. This circuit has allowed for a simple LabVIEW user interface to be programmed that contains a forward and reverse switch along with an indicator of the nozzle position. The control is accurate and has significantly reduced operating time. Furthermore, this system can be used with an automatic, closed-loop feedback controller.

IV. Control Valve Calibration

As was mentioned earlier, organ piping is an undesirable phenomenon associated with the improper control of supersonic wind tunnels. In such a circumstance, the valve opens and closes rapidly causing severe flow oscillations to propagate through the tunnel. Organ piping is named for the distinct sound fluctuations heard when it occurs. It is difficult to determine if organ piping is caused by improper control constants and a good control valve or good control constants and a control valve that needs calibration. Two cases of organ piping were purposely induced and examined. In order to safely generate organ piping conditions, the blowdown tests were carried out at subsonic conditions. Normally, plenum chambers cannot handle steady pressures for subsonic conditions (hence it is easy to induce organ piping), but it is possible to generate a steady pressure above ambient conditions if the nozzle to the test section is set to the maximum Mach number geometry thereby creating a small throat area.

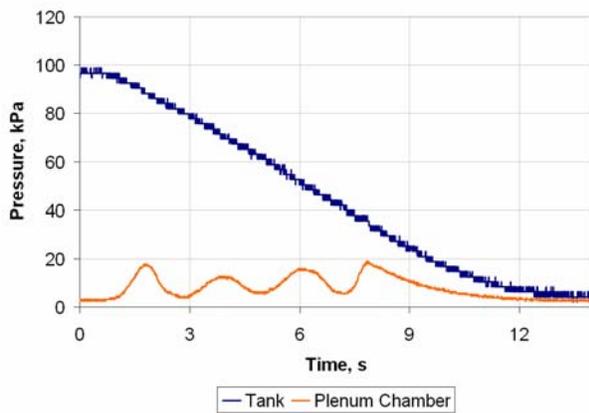


Figure 11. Tank and plenum chamber pressures versus time for first induced organ piping test.

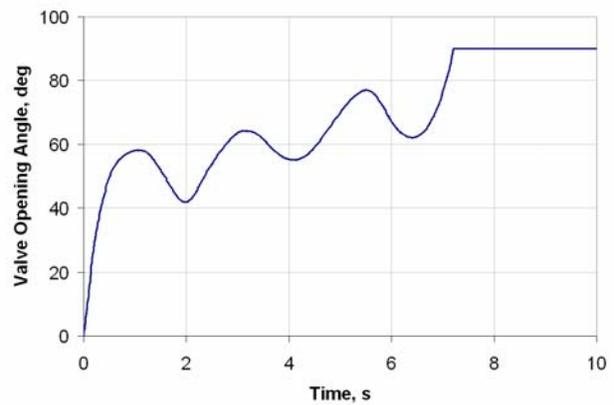


Figure 12. Valve opening angle versus time for first induced organ piping test.

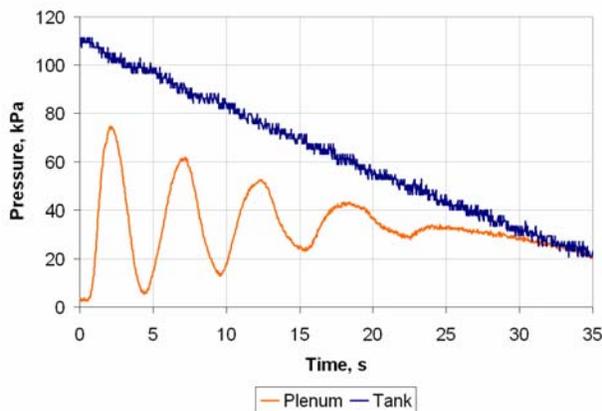


Figure 13. Tank and plenum chamber pressures versus time for second induced organ piping test.

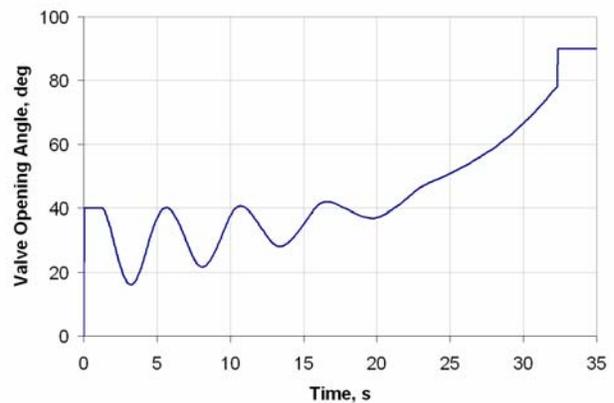


Figure 14. Valve opening angle versus time for second induced organ piping test.

Figures 11 and 12 show the results of organ piping caused by a valve that needs to be calibrated. For this test, the setpoint plenum chamber pressure was 10 kPa (gauge). However, this pressure was never maintained and the

oscillations do not appear to be converging around that value at all during the run. This is indicative of significant lag between the controller and valve because the valve does not respond well to the control signal.

Figures 13 and 14 show more significant organ piping caused by immediately opening the valve to 40° before letting the LabVIEW program take over the plenum chamber pressure control. The setpoint plenum chamber pressure was 35 kPa for this test. Although the oscillations were severe, they dampened and reached the setpoint shortly before the end of the run. This shows that for a valve in proper working order with poor control, oscillations often dampen over time. However, the oscillations can increase over time for the most severe organ piping cases.

As far as control valve calibration is concerned, industrial valve manufacturers should provide software for manipulating the internal control of the valve itself. The UT Arlington facility uses a Fisher control valve and a valve calibration program called ValveLink®. Within the valve, the current signal is transferred to a change in the pneumatic pressure which physically opens the ball valve. This process requires its own PI control so, in fact, two PI control mechanisms are in operation between LabVIEW and the valve during a blowdown run.

These industrial control valves need special calibration since the factory parameters will not result in actuation fast enough for a supersonic wind tunnel. Adding a volume booster to increase the valve travel rate is beneficial for this purpose. Figures 15 and 16 show graphs produced using ValveLink for the initial factory parameters and after a calibration routine specifically for supersonic operation. The blue lines in the figures are produced in ValveLink and are similar to a typical valve opening angle versus time plot for a blowdown run. The red lines show the actual valve angle as determined by an internally mounted potentiometer that signals back to the program. The 0–100% travel rate corresponds with the 0– 90° valve angle range. The factory parameters oscillate around the control signal and would obviously result in poor blowdown results. However, optimizing the internal control coefficients and increasing the valve travel rate with ValveLink results in much better calibration ($\pm 1\%$ signal) as seen in Fig. 16.

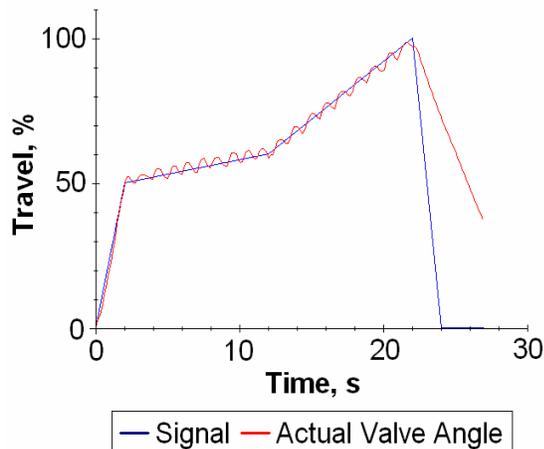


Figure 15. ValveLink signal and actual valve angle versus time for original factory control parameters.

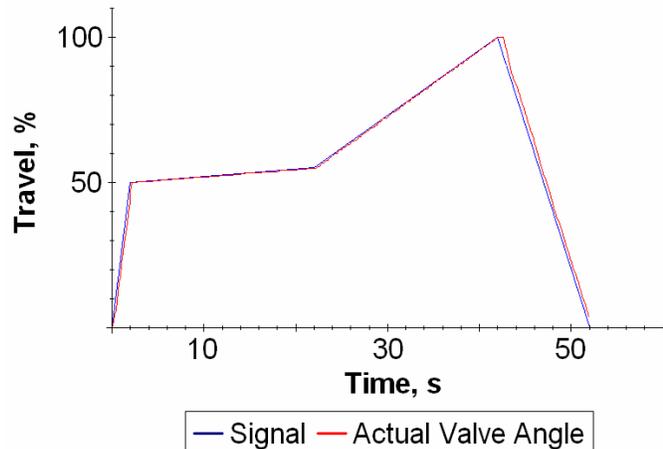


Figure 16. ValveLink signal and actual valve angle versus time for optimized supersonic wind tunnel control parameters.

While working with ValveLink, it also became apparent that setting a maximum travel rate in degrees per second for the valve would be reasonable in order to keep the signal and actual valve angles consistent with each other. The maximum valve angle travel rate has been limited to 50° per second for the UT Arlington facility. This figure is used to check for the feasibility of the simulation data. For example, in Fig. 4, the rise in valve angle for the $K_I = .2$ simulation was faster than 50° per second. However, the $K_I = .6$ simulation plotted in the same figure shows an increase in valve angle closer to the specified maximum travel rate.

V. Experimental Verification

Experimental verification has been carried out for both subsonic and supersonic conditions to show the robust control ability of the PI logic applied to a supersonic wind tunnel. The accuracy of the simulation applied to calculating accurate blowdown run times is also discussed. The supersonic tests all occurred with the same initial conditions to show the effect of varying the K_I control constant. Besides maintaining a constant plenum chamber

pressure, LabVIEW has the ability to change its control parameters during the blowdown run, which yields several new supersonic testing possibilities to be discussed.

A. Subsonic Testing and Validation

To validate the LabVIEW controller for maintaining a steady plenum chamber pressure for subsonic conditions, the nozzle throat was set to the geometry that would otherwise be used for Mach 4 runs. Figure 17 shows the results of maintaining a setpoint pressure of 10 kPa for a low storage tank pressure. The K_I control parameter was set to a high value which explains the slow increase to the setpoint pressure.

For large K_I values, the subsonic test shows that the maintained steady pressure will occur at a value slightly less than 10 kPa, a trend typical of PI control which contains an inherent offset. However, this should not be an issue with supersonic tests with high initial head pressure values where K_I can be reduced. The figure shows at between 25 and 35 seconds, the plenum chamber decreases slightly, another typical result of the PI control associated with a low head pressure. The impact of this trend should be reduced as larger pressures are used.

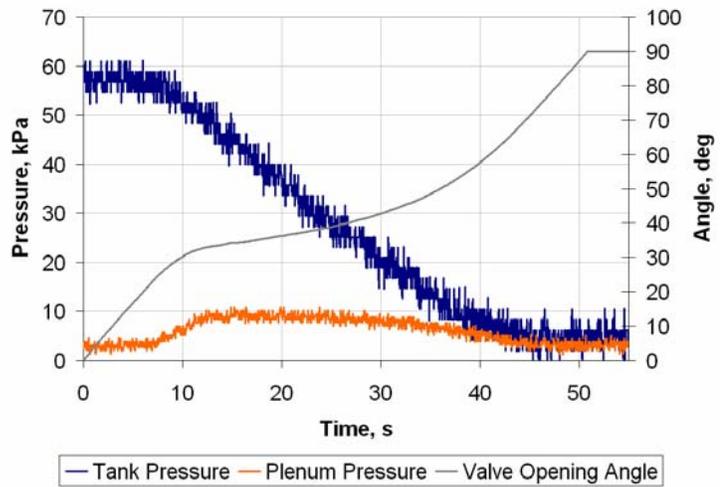


Figure 17. Tank pressure, plenum pressure and valve angle versus time for a subsonic blowdown run.

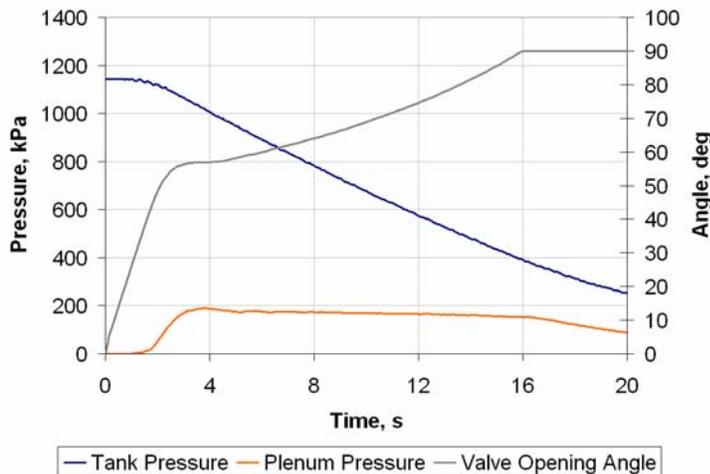


Figure 18. Tank pressure, plenum pressure and valve angle versus time for a Mach 1.5 blowdown run with $P_D = 190$ kPa, $K_I = 1.1$, $K_P = .00014$ and a control frequency of 10 Hz.

Mach 1.5 with $P_D = 190$ kPa will obviously result in longer test times with steady pressure within the $\pm 1\%$ error range.

Figures 19 and 20 show the effects of varying K_I . As was predicted in the simulation, smaller values of K_I cause the valve angle to increase faster, but are prone to overshoot and oscillations. Increasing K_I beyond 1.1 reduced the time in which constant plenum pressure is maintained. For the $K_I = .7$ case, the overshoot of the setpoint pressure is 25%. This overshoot will continue to increase as K_I is lowered and organ piping will result.

B. Supersonic Validation

Validation of the LabVIEW program at supersonic conditions was performed at a Mach number of 1.5 for constant tank and set point pressures for four runs with different values of K_I . The results from these runs show the effect of varying K_I , and all four runs produced steady pressure with an error of $\pm 1\%$.

Figure 18 shows results with a high value of $K_I = 1.1$ which reduces plenum pressure overshoot. The overshoot is not seen in the simulation, but it exists due to a small amount of lag between the computer and the control valve. Again, the plenum chamber pressure drops slightly for the last four seconds of the run, but the error between 5 and 12 s is still $\pm 1\%$ from the average pressure in that period. This run was started with about one quarter of the storage tank capacity, so longer runs at the setpoint pressure will be possible.

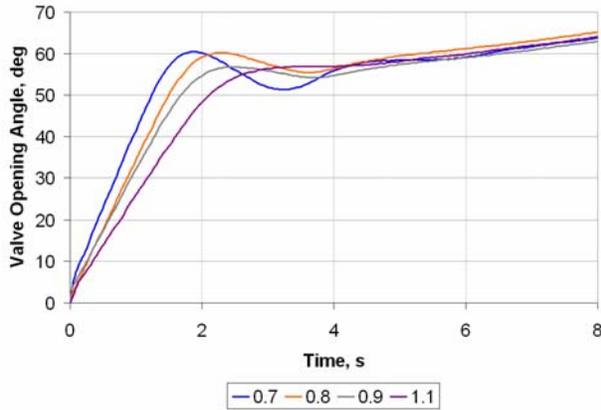


Figure 19. Valve opening angle versus time for the beginning of four Mach 1.5 blowdown runs with K_I varied.

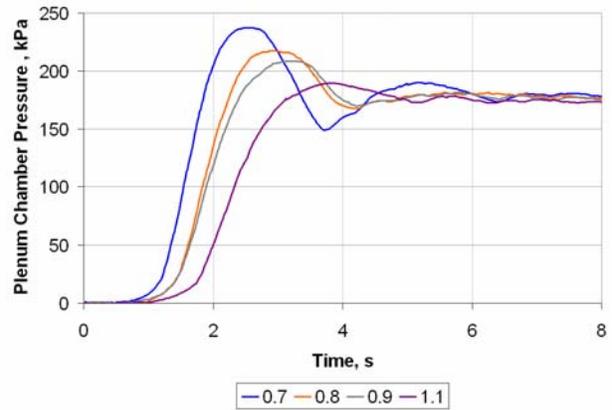


Figure 20. Plenum chamber pressure versus time for the beginning of four Mach 1.5 blowdown runs with K_I varied.

Figure 21 shows the pressures and run time for these tests versus results from simulations carried out with the same initial conditions. Here, a value of 1.3 was used for η . The comparison shows that the value of η is accurate for predicting the run time of the wind tunnel for other cases. The pressures in the figure were alike except for the rise of the plenum chamber pressure. This difference again is due to the finite filling time of the plenum chamber and the control valve lag. The simulation shows an instant increase in plenum chamber pressure at the beginning of the run, but in actuality it took two seconds for the plenum chamber pressure to begin to rise.

The values of $K_p = .00014$ and $K_I = 1.1$ should work for the full range of operational capability at the UT Arlington supersonic wind tunnel facility for a Mach number range of 1.5–4 and a maximum storage pressure of 5 MPa. When compared to the Mach 1.5 results, any combination of raising the initial storage tank pressure or increasing the test section Mach number should cause the plenum chamber to fill faster, thereby allowing K_I to be reduced. Reducing K_I causes the valve to react faster which will reduce offset and keep the plenum chamber pressure from falling towards the end of the run. Therefore, the methodology for selecting new control constants will be to first run a simulation for new initial conditions with previously validated control constants. Next, K_I can be varied to manipulate the rate of response of the control valve. Once the rate of response appears feasible, the new control constants can be tested during a blowdown run.

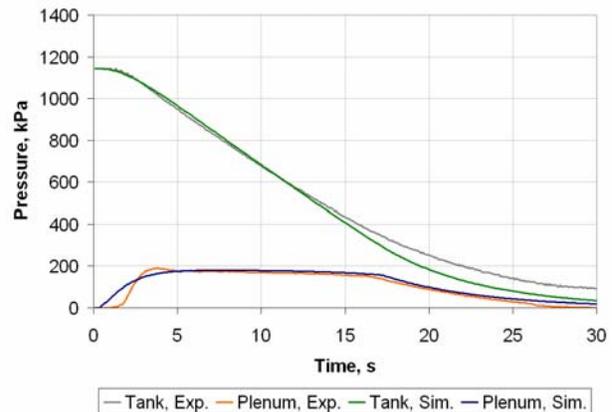


Figure 21. Plenum chamber and tank pressure versus time for Mach 1.5 simulation and experimental results.

C. Additional Capabilities with LabVIEW

LabVIEW offers an extraordinary range of possibilities for manipulating the PI controller for different blowdown conditions since the program is very easy to alter. Often, the plenum chamber pressure for a blowdown run is set well above the minimum pressure ratio for choking the nozzle flow since test models create blockage. However, once the supersonic flow in the test section is started, it is easy to program a time into LabVIEW at which the setpoint pressure will be reduced in the plenum chamber. A simulation of this strategy is shown in Fig. 22. The value of K_I can be switched at the same time to a higher value which will cause a more gradual reduction in pressure. The first benefit of reducing the pressure is that each blowdown will generate aerodynamic data for two Reynolds numbers. Also, when compared with Fig. 3, it is apparent that reducing the pressure will significantly increase the run time. Changing the plenum chamber pressure has been successfully accomplished for low pressure subsonic cases.

With the ability to control the nozzle throat motor via LabVIEW, it may also be possible to vary the test section Mach number during a blowdown. The simulation does not respond as well to this case as it does for switching the pressure, but switching the Mach number and pressure simultaneously yields good simulation results. Switching both values is easier since the valve opening angle does not have to rapidly increase to maintain the higher plenum chamber pressure associated with the first test section Mach number.

Depending on the digitizer board used, LabVIEW can output a control voltage to the valve at frequencies above 1 MHz. Therefore, it is reasonable to assume that the quality of the LabVIEW control will be increased by raising the frequency to very high values. This assumption is true to some extent, but the LabVIEW control frequency at present is limited by several factors including the error of the pressure transducer measurements and the rate at which the pneumatic control valve can operate. While the 10 Hz control frequency used for the supersonic validation tests is somewhat low, it is adequate and it is doubtful that frequencies above 100 Hz will add any benefit to the control. The $\Delta\theta$ values become very low at frequencies above 100 Hz at the time of steady pressure during a blowdown test. Therefore, it is likely they would be hidden by system noise and would not be recognized as a change in the current signal.

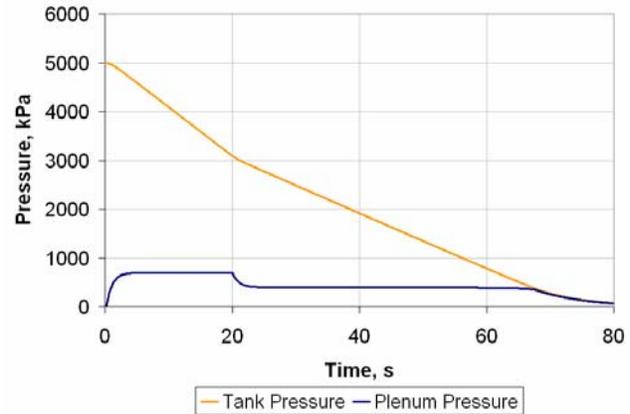


Figure 22. Plenum chamber and tank pressure versus time for Mach 2.5 simulation where the setpoint pressure is switched 20 seconds into the run.

VI. Conclusions

In summary, a proportional-integral control routine as developed in a LabVIEW environment provides sufficient control for a supersonic blowdown wind tunnel. Considering the number of pressure transducers and the performance of the pneumatic control valve, the error seen in the plenum chamber pressure during a blowdown run is minimized with the control program for the UT Arlington facility characteristics. With an understanding of the effects of the PI control constants using the simulation and experimental results, the LabVIEW program can be immediately used for different initial blowdown conditions. LabVIEW offers the ability for the user to edit the control program^{††} to perform a variety of functions both before and during a blowdown run. Additionally, the construction of simple circuits can extend the analog output capabilities of the program for controlling high power mechanisms like a nozzle throat motor.

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^{††}The LabVIEW and simulation programs will be placed on the National Instruments online code sharing community as well as the UT Arlington Aerodynamics Research Center website, <http://arc.uta.edu>.

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