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PRE-PROGRAMMED CONTROLLER FOR A SUPERSONIC BLOWDOWN TUNNEL

J. Matsumoto, F. K. Lu and D. R. Wilson

Aerodynamics Research Center
The University of Texas at Arlington
Arlington, Texas 76019

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Abstract

A PC-based pre-programmed controller was developed for a supersonic blowdown wind tunnel with short run time. It starts the tunnel very quickly without any overshoot of the stagnation pressure. The controller system consists of a pressure transducer, a multifunction PC board and an automatic valve. An ideal valve opening profile for a particular test is developed based on preceding test results at the exact same test conditions of throat area of a nozzle and storage tank pressure. The profile is stored in the system memory before a test and the multifunction board sends an analog output to the automatic valve during a test. After several tests and corrective interpolations, the pressure disturbances in the plenum chamber are typically reduced to one percent of the stagnation pressure.

Introduction

Blowdown supersonic wind tunnels are operated with a constant stagnation pressure P_0 in the settling chamber, with control usually by one or more pressure regulators. The regulator valve is opened progressively wider during a run as the storage tank pressure continuously decreases. The method for controlling the valve opening has evolved from a primitive manual operation to highly sophisticated neural net controllers in the last half century.[1] Most of the recent systems developed are based on real-time controllers. Generally, a real-time feedback loop such as a proportional gain, time integral and time derivative (PID) controller works very well with long-duration wind tunnels. For this case, the storage air pressure decreases slowly enough to allow devices with slow time response sufficient time to respond to the changing pressure. However, when the storage volume is limited, a real-time loop may fail to keep up with the rapid pressure decay. In addition, very small time delays due to the motion of the mechanical elements of a valve become critical. Under such circumstances, alternative approaches, such as neural networks may be needed. A pre-programmed controller is proposed as a simple alternative to a neural net controller to achieve a fast responding system. It offers the capability of starting the wind tunnel quickly and providing a stable flow, overcoming the slow response of a PID controller.

Improving the controller of a wind tunnel can significantly improve the flow quality in a test section. For example, good flow quality is essential to provide crucial data to verify computations. The required accuracy of flow may vary with the type of tunnel and the test. For a typical airplane test, an error of less than 1.0 percent in C_d and C_p is usually sufficient. To meet those criteria, the Mach number in the test section must stay uniform at about ±0.3 percent at Mach 3.[2,3] Unlike the Mach number, it is difficult to maintain a constant Reynolds number in a blowdown tunnel. This is because the temperature of the air in the storage tank drops during a test. Some further comments on constant Reynolds number testing using the novel controller is discussed later.

The controller was tested at Mach 2.5 and a stagnation pressure of 827 kPa for a short-duration supersonic blowdown tunnel. It was able to stabilize the stagnation pressure to within 1 percent. After a brief description of the facility, the difficulty using a conventional PID controller for short-duration facilities is discussed. The hardware and software of the new control system is then described with preliminary test results.

Facility

The University of Texas at Arlington has developed a sub-scale blowdown wind tunnel for aeropropulsion experiments (Fig. 1).[4] The tunnel has a Mach number range of 1.5 to 4, a Reynolds number range of 50~100 x 10^6/m and has up to 2 s of usable run time. The cross section of the nozzle exit is 0.15 x 0.15 m and is enclosed by a 0.45 m long, semi free-jet test section with glass windows on the sides. The wind tunnel was operated using a 0.15 m diameter, pneumatically-driven automatic ball valve (Fisher Model V200), which controls the flow from the storage tank to the plenum chamber to maintain a constant stagnation pressure as close as possible to a set point pressure P_{SP}. The storage tank has a volume of 1.78 m^3 and it was filled with compressed, dry air at 4.8 MPa before a run. When initially configured, the automatic valve was opened using a digital valve controller (Fisher DVC-5000) with a PID control algorithm to adjust the pressure in the plenum chamber to a set point. A pressure transducer and a thermocouple were installed in the plenum chamber about 0.3 m upstream from the supersonic nozzle (2.4 m downstream from the automatic valve) to measure the stagnation pressure and temperature (Fig. 2). The upper part of the figure shows a schematic of the PID controller. Note that only the signal from the pressure transducer was transmitted to the PID controller and compared with the set point. The corrective output is then transmitted to the valve.

A serious problem was encountered with the above control configuration during shakedown tests in that severe pressure oscillations occurred in the plenum chamber. The reasons for the oscillations were the slow response of the automatic valve, the slow processing speed of the digital PID controller, and the time delay Δt of pressure data transmitted to the controller. Compounding these problems, about 0.5 ~ 1.5 s of delay was detected between the control output and the response of a pressure change in the plenum chamber. The motion of the automatic valve was too slow. It needed almost 10s to open fully and even more time to close. To eliminate this problem, the automatic valve was tuned by adding two dome regulators, which increased the mass flow rate of the driver air. After the modification, the valve opened in 2 s and closed in 4 s. Although the pressure oscillation was somewhat reduced, the real-time PID controller was still unstable mainly because of the input time delay (Fig. 3). A similar problem is also seen in a blowdown tunnel with long run time as a sinusoidal pressure fluctuation in the steady state.[5] Further, the short run time, which was not much longer than the time delay, made the system impossible to stabilize. One approach to overcoming this problem is to implement a transfer function of the uncertain time delay in the feedback control loop with a weighting function. This is known as a multiplicative uncertainty representation (Fig. 4).[6] The weighting function is found by trial and error and it guarantees the stability of the system when the time delay falls within a certain range. However, although this method gives some robustness to the system, it does require a considerable settling time. To address this problem, the pneumatic signal to the automatic valve was boosted to shorten its response time and a PC-based pre-programmed controller was developed to replace the PID controller.

Pre-programmed Controller

Unlike a PID controller, a pre-programmed controller is not truly a real-time system. The opening profile of the automatic valve must be scheduled before a test. During a test, the valve opens according to a pre-determined schedule. The advantages of having a pre-programmed controller are that it can compensate for the time delay of inputs and slow response devices, it can shorten the starting process, and it provides a unified control and monitoring system. The disadvantage of this approach is that it takes several training test runs to optimize the performance. Nevertheless, the gains far outweigh this disadvantage, provided that care is taken during the training exercise to ensure safe operation. Through a series of experiments using consistent storage tank pressure and nozzle setting for all training runs, it is possible to find an ideal valve opening profile for a desired set of test conditions.

At first, the initial guess of the control profile was made manually as a series of voltage signals ranging from 0 to 10 V that represent the opening of the automatic valve of 0 to 100 percent. Next, a multifunction I/O board (National Instruments PCI-MIO-16E-4) was initialized and the control profile was stored in the host memory. To start a test run, the I/O board was triggered. Then it transmitted an analog output to the automatic valve at a rate of 500 data/s. The actual position of the valve was closely matched to the output signal by the PI controller within the automatic valve. The plenum pressure and plenum temperature, the static pressure at the nozzle exit and the storage tank pressure were measured with a data acquisition system, converted to engineering units and stored on the hard drive of a PC during an experiment at 1 kHz/channel. After an experiment, the stagnation pressure was compared with the control signal to estimate a better signal. The control signal optimization code and the wind tunnel operating software was written in Visual Basic (Microsoft) and visual instrumentation tools were implemented using Component Works (National Instruments). The control profile was optimized by repeating a test run and performing an iterative computation process.

The valve opening profile $E(t)$ was separated into two regions, namely, a fast starting process and a relatively slower steady process as shown schematically in Fig. 5. The starting process is typically less than 2 s. Within this time, the valve must open rapidly from a fully closed position to one that yields the desired stagnation pressure. Thus, the valve must open rapidly at first and opens more slowly as the stagnation pressure approaches the set-point, to achieve an almost constant acceleration of the valve from the starting process to the steady process. The functional relationship

$$E(t) \propto 1 - 1/(1+ct)$$

was found to model the valve starting process well. The shape of the profile was unchanged and the opening of the valve at $t = 2$ s $E(2)$ and the slope $E'(2)$, was iterated. In the steady process ($t > 2$ s), the valve was opened further in a controlled fashion to maintain a steady stagnation pressure. The deviation of the stagnation pressure was gradually eliminated with test runs and training processes which are explained next.

Time Delay

Finding the time delay Δt and eliminating its effect is the core of this controller principle. It took over one second for the plenum chamber pressure to increase after the initial signal was transmitted to the automatic valve (see Fig. 9). This time delay became smaller as the stagnation pressure reached the set point. It could be determined experimentally run for a particular setting of nozzle throat area, tank pressure and set point pressure. At the end of the starting process of a run, the opening of the automatic valve was kept constant. This resulted in a subtle pressure decrease of the stagnation pressure since the storage pressure was continuously dropping. After a test, the stagnation pressure around $t = 2$s was closely modeled by third-order least-squares polynomial fit. The time difference between the first pole of the fitted pressure curve and the end of the starting process ($t = 2$ s) yielded the time delay at the time $\Delta t(2)$. This time delay at $t = 2$ s was used in the steady process, since it stays fairly constant during the process.

Training Process

A training process was performed after each test run to find the profile of a next run. When the initial guess of the profile is poor, it takes as many as 8 test runs and training processes to reach to the desirable shape. But after a successful training at one test condition, the number of training runs that is required for finding a profile $E(t)$ for a new test condition is expected to be smaller. After each test run, a correction $DE(t)$ was added to the last profile $E(t)_{old}$ as follows:

$$E(t)_{new} = E(t)_{old} + \Delta E(t)$$

$DE(t)$ was calculated by the converging factor CF and the error in the stagnation pressure; the difference between the set point pressure and the stagnation pressure, as follows:

$$\Delta E(t) = CF \cdot \{P_{SP} - P_0(t - \Delta t(2))\}$$

Comparing two preliminary test results of the control profile and the stagnation pressure, the converging factor is defined as

$$CF = \frac{dE(t)}{dP_0(t - \Delta t(2))}.$$

Note that the CF gives the response of the stagnation pressure dP_0 to a change of the control profile dE. In this way, CF does not necessarily have to be the local true value. As the CF gets closer to the true value, the control profile converges more quickly to the ideal profile. This value stays almost constant in the steady process except the final several tenths of a second where the motion of the automatic valve cannot catch up with the decrease of the tank pressure, and it differs slightly for each run. The time delay and the converging factor were renewed for each run until the error in the stagnation pressure at t = 2s was considerably small. The flowchart of the training process is shown in Fig. 6.

The pressure data was smoothed by a sixth-order least squares fit to eliminate low-order discontinuities in the new profile:

$$P_0(t - \Delta t(2)) = \sum_{i=0}^{6} a_i t^i$$

A sixth-order fit can smooth up to three undesirable pressure oscillations in the steady process, which is adequate for our purpose. The pressure data recorded at time $t-\Delta t(2)$, represented by $P_0(t-\Delta t(2))$, was compared with the control signal transmitted at time t, $E(t)$. Shifting the stagnation pressure by $-\Delta t(2)$ eliminates its time delay.

Results and Discussion

Test runs were conducted at Mach 2.5 with a storage tank pressure at 4.8 MPa. The set point pressure was 827 kPa, which provides a pressure ratio across the nozzle that exceeds the minimum starting ratio by a comfortable margin. Before the iterative processes, two test runs were done to roughly estimate the relation between the control signal and pressure rise at the operating condition. The valve was opened 40 and 45 percent in 2 s in the starting process and then it was exponentially opened in the steady process till the tunnel exhausts all the available air. The time delay $\Delta t(2)$ was estimated at 0.63 s. Comparing the last two results of the control signal and the stagnation pressure without the time delay, the converging factor of the next run was found, as illustrated in Fig. 7. From this third run, the training process was used to better estimate the control profile. After four additional tests and interpolations (Fig. 8), the steady state error of the stagnation pressure is typically reduced to 1 percent of the stagnation pressure (Fig. 9). The stagnation pressure is observed to increase about 1.5 s after the transmission of the first signal to the valve. It then rises to the set point pressure in less than 1 s. After 1.6 s of steady operation, the valve is fully open, and can no longer maintain a set-point pressure.

The stagnation temperature dropped significantly during a run due to the adiabatic expansion of the air in the storage tank. When the storage tank pressure is much higher than the stagnation pressure, the effect is more severe. It affects the Reynolds number and the Mach number of a test. For example, Reynolds number increases 6.7 percent from 82.5 x 10^6/m at Mach 2.48 as the stagnation temperature drops from 21.1 to 8.9 °C. On the other hand, the Mach number change is negligible from second-order effects arising from changes in boundary layer thickness. The temperature drop can be suppressed by installing heaters in the plenum chamber or crumpled metals in the storage tank.[7] However the effectiveness of such devices is in doubt for the short run time tunnel. To maintain a constant Reynolds number without keeping the stagnation temperature constant, the stagnation pressure must drop to compensate the effect. This can be accomplished quite easily using the PC based pre-programmed controller. The constant set-point pressure is modified in such way that it decreases 51 kPa during the steady process in case of Mach 2.5. In a sense, the small change of the high Reynolds number of a turbulent flow does not affect the outcome of a test but can provide better test conditions.

Summary and Conclusions

A PC-based preprogrammed controller was developed to overcome the shortcomings of a conventional PID controller for a wind tunnel with minimal air storage. It starts the tunnel quickly without any overshoot of the pressure while utilizing the existing devices. This controller will be tested further to investigate the minimum stagnation pressure error and optimum valve opening profile for Mach number range of 1.5~4.0.

Acknowledgements

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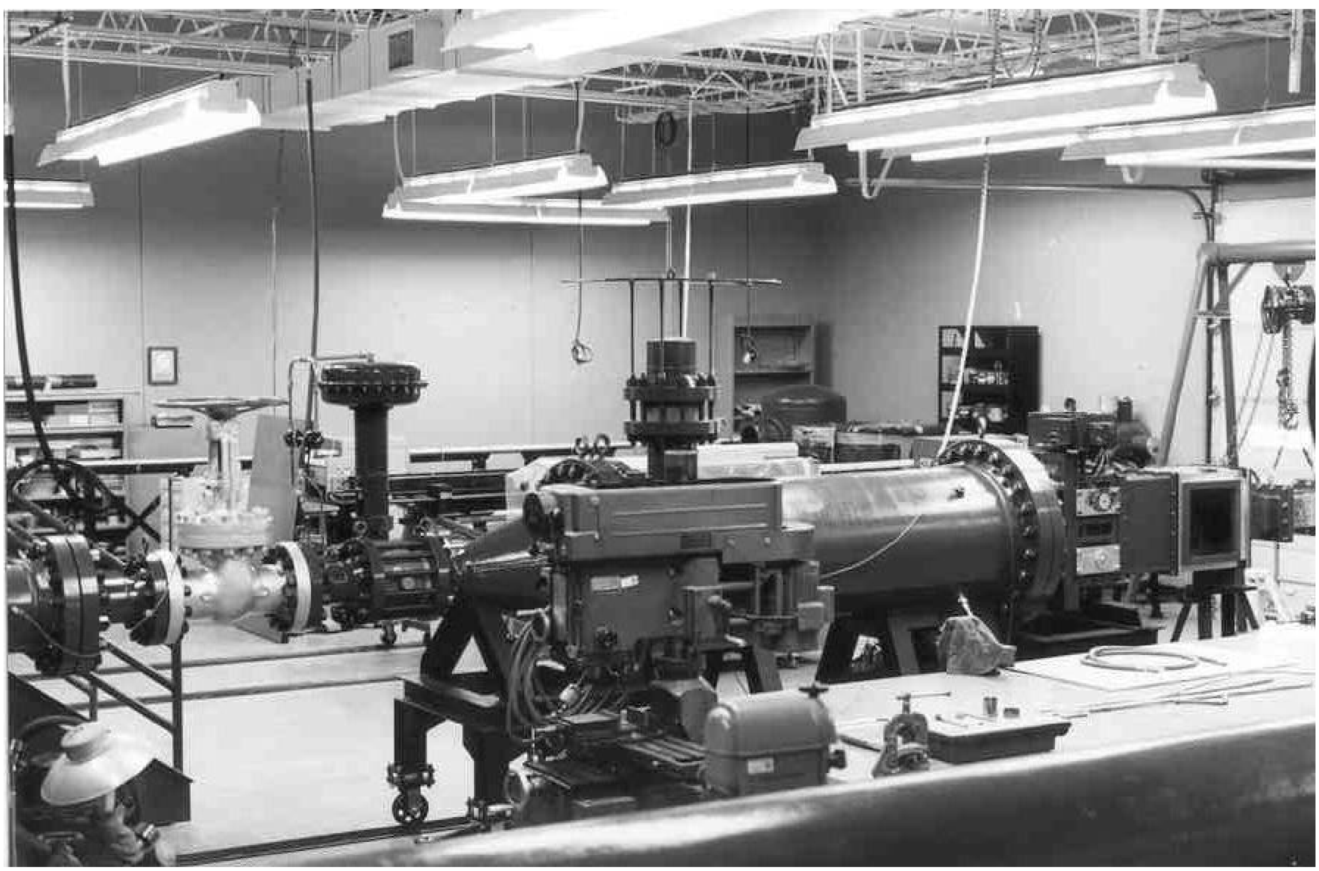

Figure 1 UTA 6x6 in. supersonic blowdown wind tunnel.

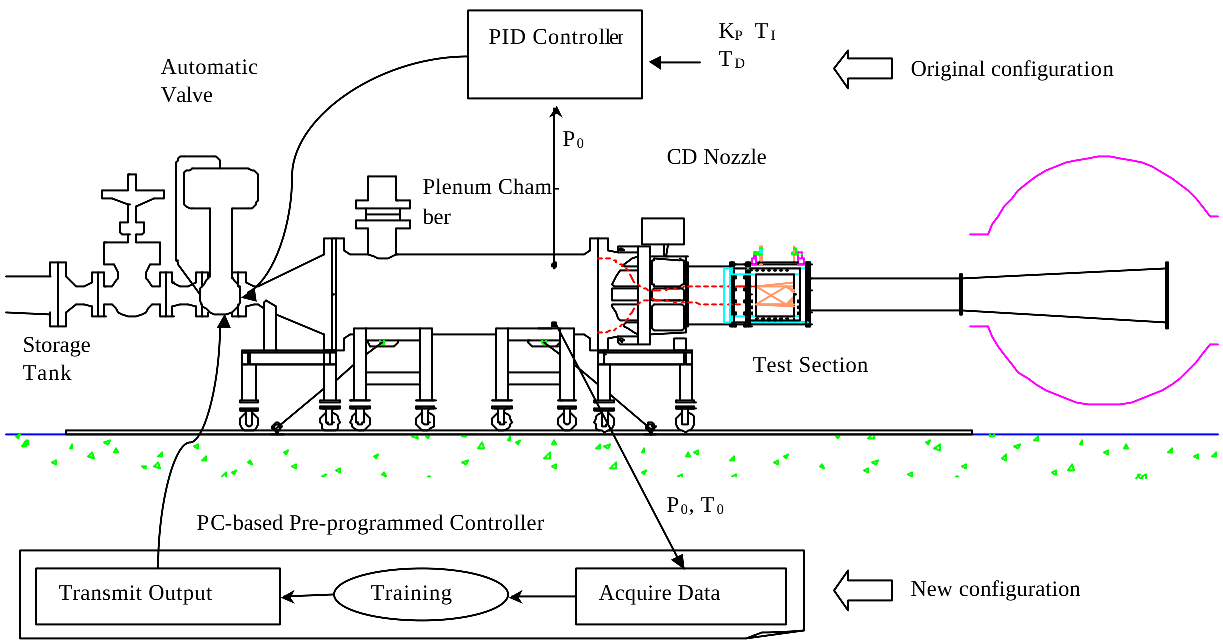

Figure 2 Schematic of the control system.

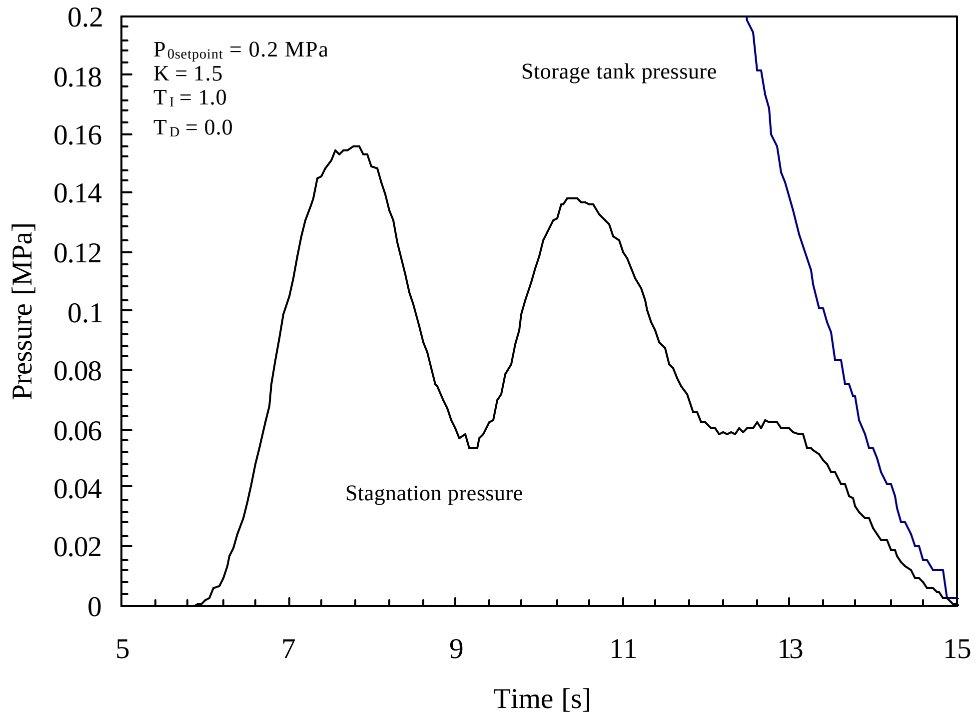

Figure 3 Typical test result using a PID controller.

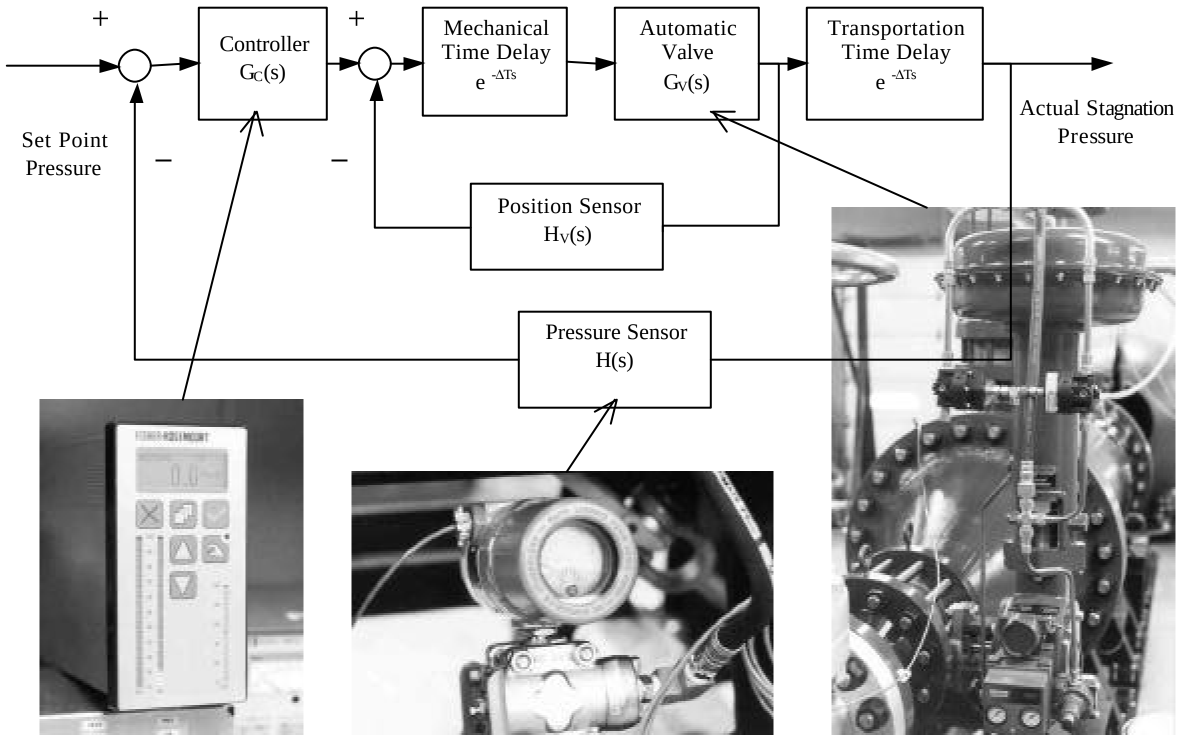

Figure 4 PID control system with time delay.

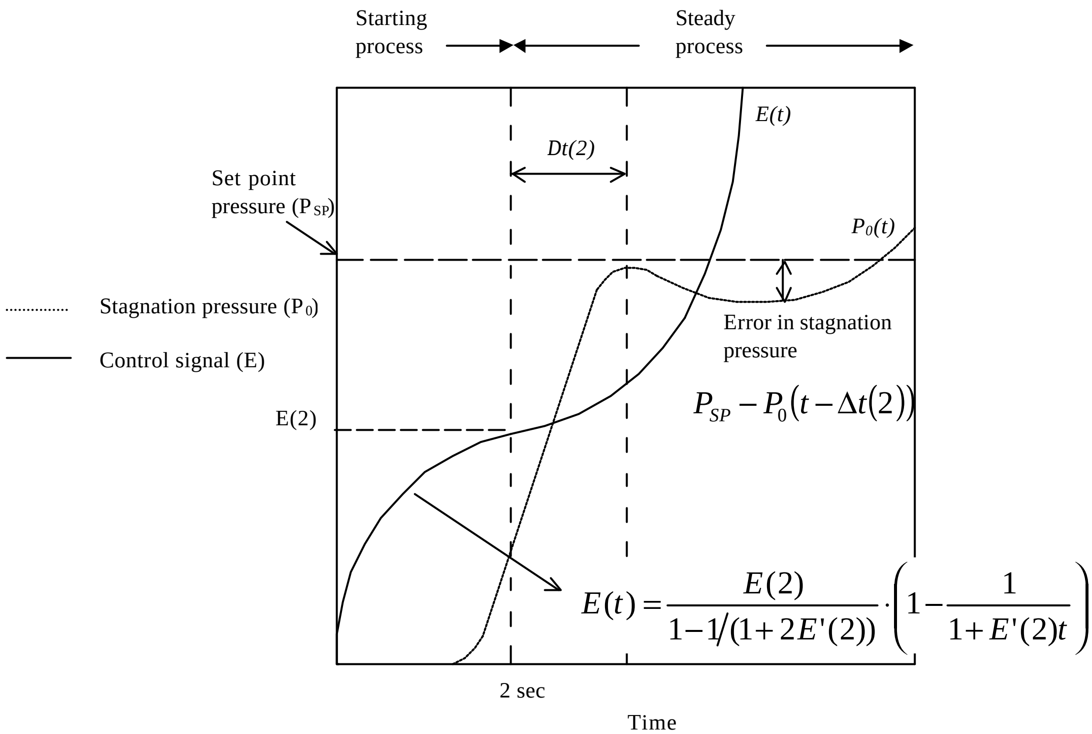

Figure 5 Schematic of a valve opening and a stagnation pressure profile.

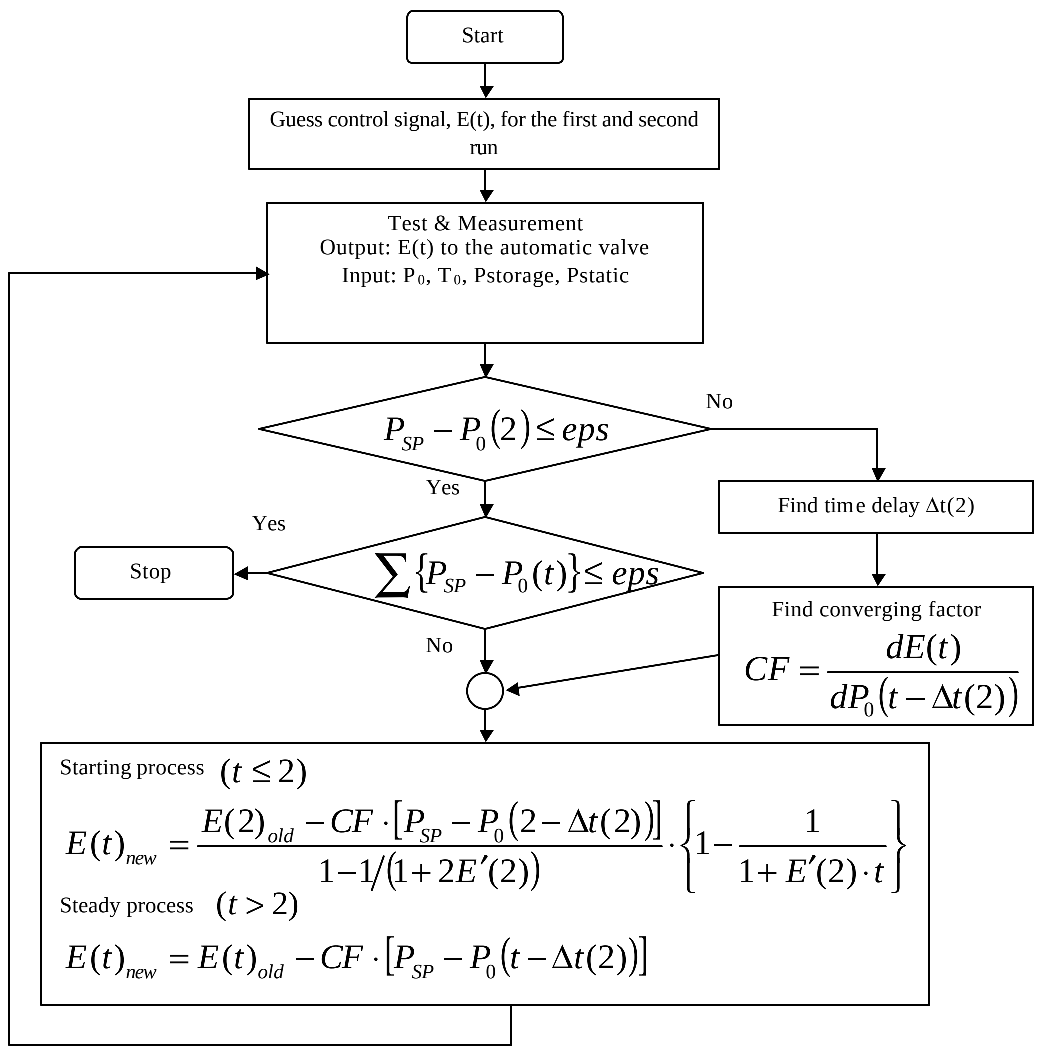

Figure 6 Flowchart for calculating the control signal.

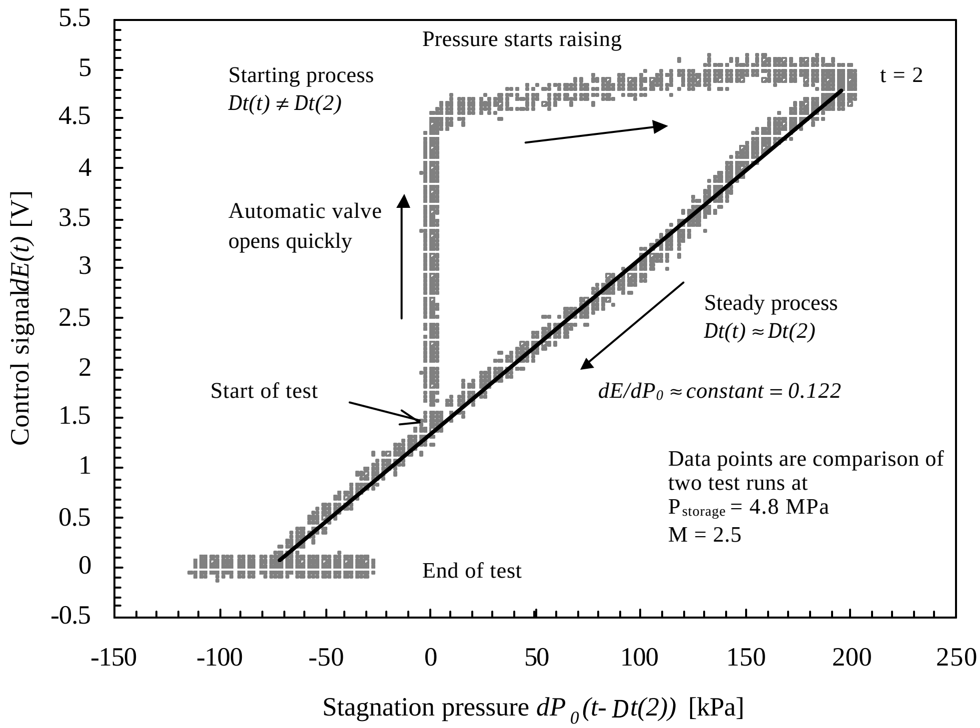

Figure 7 Variation of the stagnation pressure with changes in the control signal.

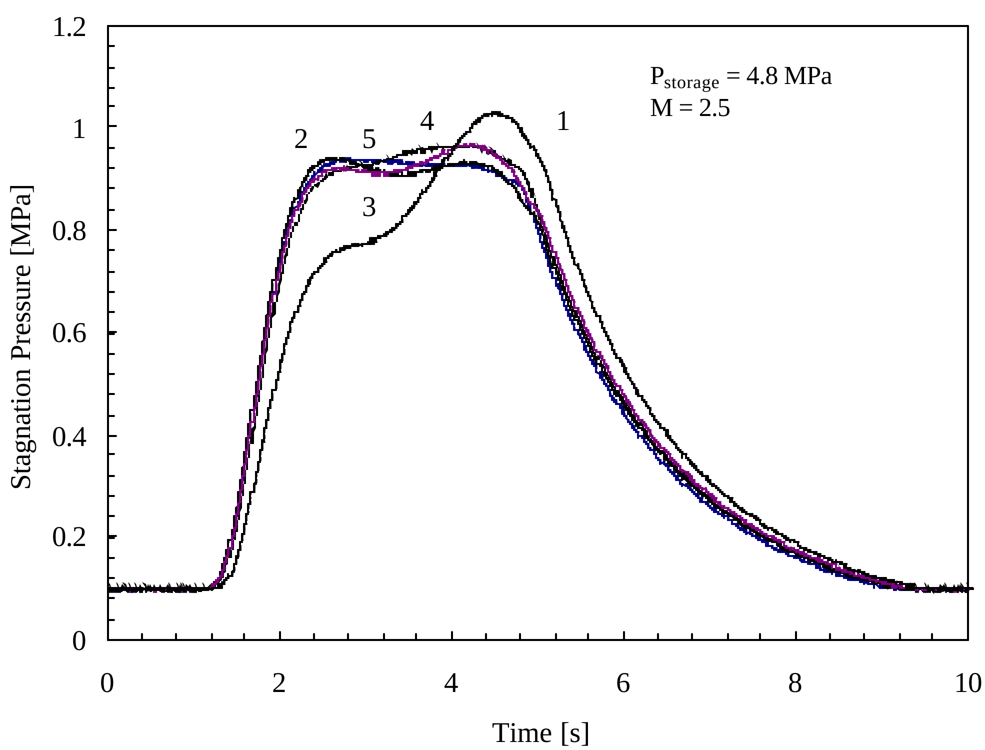

Figure 8 Stagnation pressure trace of five training processes.

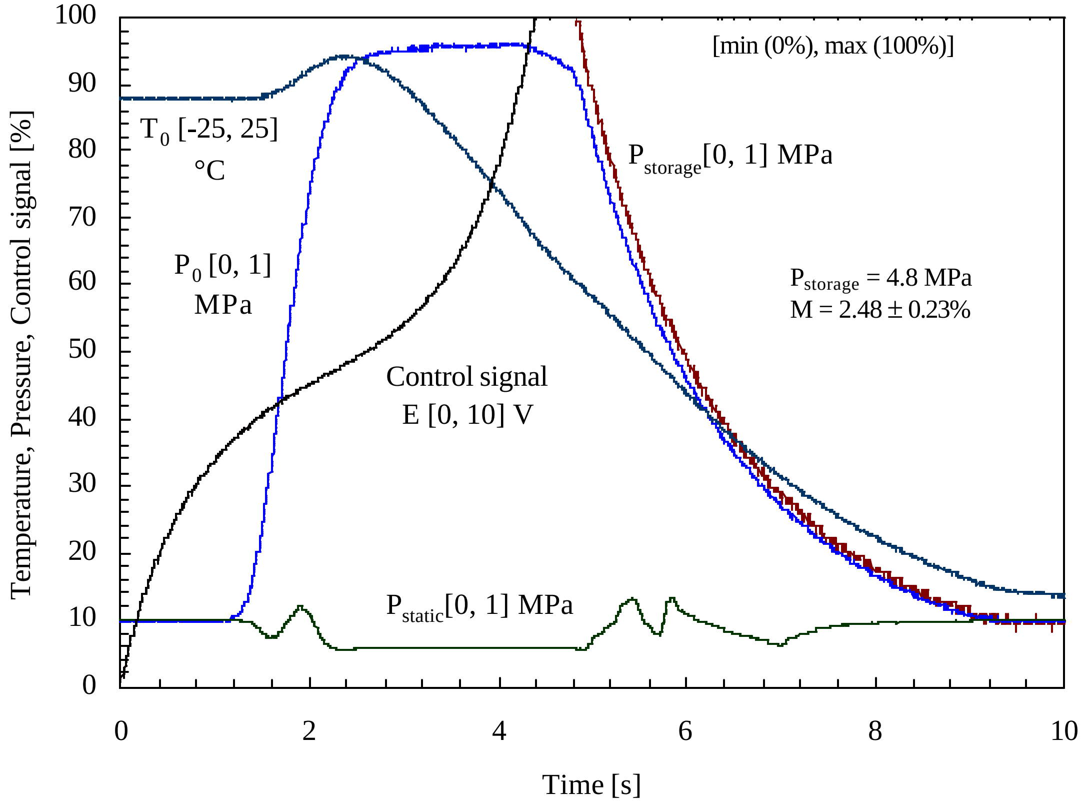

Figure 9 Pressure and temperature trace after training processes.