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Model-Based Stagnation Pressure Control in a Supersonic Wind Tunnel

The flow parameters control in wind tunnels is an area of intense research in recent years, with the aim of improving quality and efficiency of the wind tunnel operation. In this paper, an attempt is made to contribute to a better understanding of the stagnation pressure control in supersonic blowdown-type facilities. The stagnation pressure control strategy in the VTI Belgrade T-38 wind tunnel is discussed. An improved mathematical model for a supersonic wind tunnel is suggested and applied to the T-38 facility. Comparisons of simulation and experimental data are made to demonstrate accurate prediction of the facility response in supersonic flow conditions by the mathematical model. The model is used to incorporate a modified feedforward control in the original T-38 wind tunnel control system. The actual wind tunnel tests confirm model-predicted decrease of flow stabilization time and increase of available measurement time, bringing significant improvement in the wind tunnel operation efficiency.

Keywords: supersonic flow, mathematical model, blowdown wind tunnel, stagnation pressure, lumped parameter model, finite difference method, feedforward control.

1. BACKGROUND

Wind tunnels are experimental installations designed for aerodynamic studies of reduced-scale models, based on achieving geometric, kinematic and dynamic similarity with full-scale objects. Aerodynamic forces generated between the air and the object depend on two important properties of the air: compressibility and viscosity. Similarity parameters used to model these effects are Mach number and Reynolds number, respectively.

There are several different ways to classify wind tunnels, but they are most often designated by the Mach number, in order to emphasize relative importance of compressibility. According to such classification, supersonic wind tunnels are capable to achieve Mach number between 1.2 and 5.0. The design of a supersonic wind tunnel always includes a convergent-divergent nozzle, whose geometry uniquely determines the Mach number at the nozzle exit. Since wind tunnels are designed for a Mach number range, variable-geometry nozzles are used. Throughout the wind tunnel history there were several nozzle designs applied, including fixed-block design, plug-type and grating-type designs, but the most versatile method of obtaining the variable geometry is the flexible nozzle [1]. The flexible plates are contained between two parallel flat walls and they are bent to the required shape for the desired Mach number. A method for obtaining nozzle geometry is well-established [2]. Complex numerical simulations have been enabled by fast computers recently, but they have application mainly in fine tuning of the geometry obtained by the fundamental aerodynamic calculation.

While Mach number similarity in a supersonic wind tunnel is achieved by nozzle design, Reynolds number similarity requires a different approach. When testing a reduced-scale model, it is necessary to increase the Reynolds number to improve similarity with the full-scale object. One of the ways to achieve that is raising the dynamic pressure by increasing air density, namely raising the stagnation pressure. This principle of achieving Reynolds number similarity is used in pressurized blowdown-type wind tunnels [3].

The successful operation of a supersonic pressurized blowdown wind tunnel and achievement of the always more stringent requirements for measurement quality are hindered by several challenges [4], most of them closely related to the stagnation pressure control, which includes establishing and maintaining the desired stagnation pressure value during a wind tunnel test.

There are two distinct trends noticeable in this research area. The first trend includes development of wind tunnel mathematical models based on physical principles, to predict the required facility setup, incorporate feedforward control and augment a standard proportional-integral-derivative (PID) type control system. In one of the first structured studies of the control problems of compressible flows [5], an isentropic mathematical model of the flow in a supersonic wind tunnel was developed for the open-loop system characteristics and was linearized for the design of a proportional-integral (PI) controller. The resulting performance of the supersonic wind tunnel was found to be quite good, with stagnation pressure variations typically held to within 1 to 2 percent. Basically the same isentropic mathematical model is used in [6] to identify a PI controller, and improvements were expected based on using modern numerical simulation tools, as well as more advanced hardware and software platform. However, the stagnation pressure regulation accuracy of 1% did not bring a significant improvement.

A pre-programmed controller [7] demonstrates good accuracy, but several attempts are needed before it can be calibrated for a new Mach number and stagnation pressure combination. In addition, the feedforward controllers that operate at different conditions may not be robust enough to accommodate the varying pressure and mass flow requirements safely.

The second trend refers to development of highly sophisticated controllers based on adaptive control, fuzzy logic, neural networks or genetic algorithms, to overcome shortcomings of existing mathematical models. In [8], [9], [10] and [11] different types of sophisticated controllers are used with the intention to improve the stagnation pressure control accuracy. The accuracy of 0.1% is indicated, but at the cost of higher complexity of these controllers, as well as complicated adjusting procedure during the training stage. In [12], an artificial neural network is used for finding the optimum membership functions of the fuzzy logic controller, but experiments with the identified controller demonstrated large wind tunnel starting pressure overshoots.

Since the simplified mathematical models combined with various control algorithms did not bring expected results, the interest in wind tunnel modelling reappeared in recent years. In addition to traditional feedforward methods, more sophisticated model-based control methods are currently under investigation, aimed to not just facilitate efficient changes between steady-state points, but to control transition of the wind tunnel between these points [13], [14]. The models have also found application in facilitating wind tunnel design efforts [15].

Efforts were made recently to develop advanced mathematical models for different aspects of behaviour of subsonic wind tunnels. A model for the thermal behaviour of a subsonic wind tunnel [16] was used to control temperature in the actual wind tunnel [17]. A model that deals with the short-time-scale changes in pressure and other flow parameters in response to changes in control inputs was developed and validated via comparison with experimental measurements [18].

There are no many examples of refinements of the basic isentropic model [5] of the flow in supersonic wind tunnels. In [19], heat regenerators inside the supersonic wind tunnel storage tank were modelled and included in the overall facility mathematical model to predict improvement in the temperature variation during wind tunnel tests.

In this paper, an improved mathematical model of a supersonic wind tunnel is suggested and applied to the VTI Belgrade T-38 wind tunnel. The predictions of the model are validated by comparison with the T-38 wind tunnel experiments. The model is then used to predict the facility setup required to achieve the improved stagnation pressure control and incorporate modified feedforward control into original control algorithm.

Wind tunnel tests with the modified control and model predictions are well-matched, with relative deviation between experimental data and model results for stagnation pressure less than 1%. Significant decrease of flow stabilization time is achieved, bringing increase of available test time up to 6 seconds in comparison to the previous algorithm, depending on Mach number and stagnation pressure combination.

2. SUPERSONIC BLOWDOWN-TYPE WIND TUNNEL STAGNATION PRESSURE CONTROL

2.1 Wind tunnel test facility

The VTI Belgrade T-38 wind tunnel (Figure 1) is a blowdown-type test facility equipped with a variable Mach number nozzle and a 1.5 m × 1.5 m test section. The Mach number range is 0.2 to 4.0 with Reynolds number up to 100 million per metre [20].
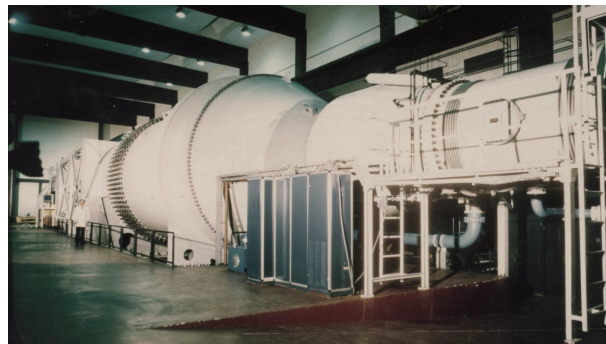

Figure 1. The VTI Belgrade T-38 wind tunnel

Flow is established by the discharge of the 2600 m³ air storage tank, pressurized up to 2 MPa, through the installation into the atmosphere (Figure 2). The stagnation pressure range is from 0.12 MPa to 1.5 MPa, depending on Mach number. Available run time is from 6 s to 60 s, depending on Mach number and stagnation pressure combination.
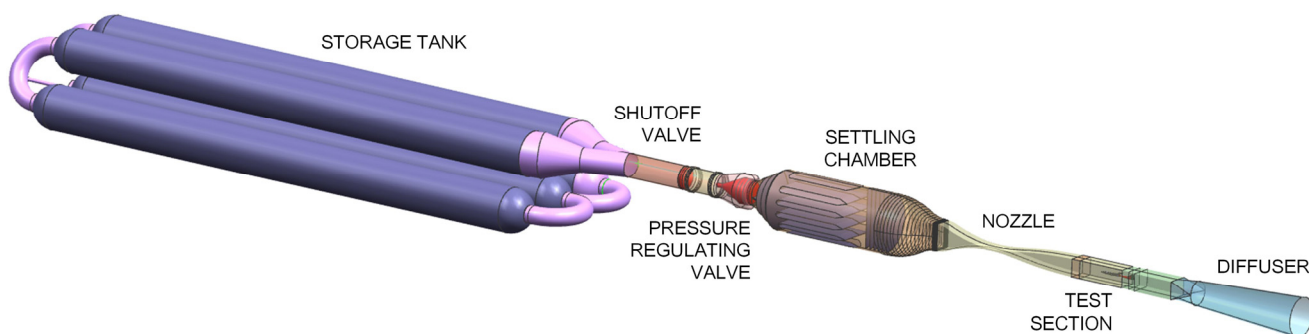

Figure 2. Simplified 3D model of the T-38 wind tunnel

During a wind tunnel test, a basic requirement is to maintain the desired values of Mach number and stagnation pressure within pre-defined limits [21], [22].

Desired Mach number in supersonic regime is set by means of a two-dimensional variable geometry nozzle, with upper and lower flexible 11.0 m × 1.5 m plates being moved between two rigid side plates by 19 jack stations with 38 hydraulic cylinders and 76 screw jack stops powered by 38 electric motors [23].

Desired stagnation pressure is controlled by a pressure regulating valve, an annular valve with the central element moving along the wind tunnel axis and changing air mass flow through the installation. The valve geometry is a result of an aerodynamic calculation carried out in the wind tunnel design phase and consists of three segments – an exponential segment between two linear ones. The valve stroke is from 0 to 0.5 m, corresponding to the valve exit cross-section area from 0 to 1.8 m^2.

Storage tank pressure and temperature are measured at the tank outlet. Stagnation pressure and temperature are measured at the settling chamber outlet (Figure 2).

2.2 Stagnation pressure control strategy

The stagnation pressure is first achieved and then regulated for the duration of a wind tunnel experiment. Regulation normally involves maintaining a set point stagnation pressure as the storage tank pressure falls. Important requirements are the following:

- Fast start-up. This is critical to efficient operation of the facility. In essence, this means that the flow must be established throughout the circuit to the set point, as quickly as possible. If not, valuable run time may be lost.
- Close regulation. Following start-up, stagnation pressure must be close to the set point for the duration of the wind tunnel test.

The above requirements must be met over a wide range of operating conditions.

Stagnation pressure control is achieved by modulation of the pressure regulating valve (Figure 2). The position of the valve is related to the pressure set point via a double-loop scheme. An inner loop is the pure valve position control via an electro-hydraulic servo system according to a valve position set point generated by the control algorithm in an outer loop.

Stagnation pressure control in the T-38 wind tunnel is divided into four consecutive phases [28] during a test (Figure 3).

- Phase 0: Initialization.
  During this phase, immediately before the pressure regulating valve opening, the calculations relevant to start-up are made. These calculations include determining the initial valve position, the nozzle throat area and feedback control constants.

- Phase 1: Start-up.
  During this phase, the valve is commanded to open to the position calculated in Phase 0. The valve

effective area required for the start-up is determined from the storage tank pressure, stagnation pressure set point, Mach number and the settling chamber fill-up time.

- Phase 2: Feedforward control.
  The purpose of this phase is to allow the flow to stabilize close to the set point condition. This is accomplished by closing the valve to an equilibrium hold position. The effective valve area is simply that estimated to sustain steady flow conditions, and it is the feedforward value used throughout the remainder of the test. This means that the valve will open slightly as tank pressure falls, so it is not really a "hold". The switch to the next phase is made on the basis of achieving a fraction of set point stagnation pressure.

- Phase 3: Feedforward and feedback control.
  When this phase is initiated, it is assumed that the flow is reasonably steady. Thus it should be possible to trim out any deviations from set point conditions. The valve position required to do this is calculated using the sum of the feedforward position, calculated as in the Phase 2, and a feedback position according to the difference between the current and set point stagnation pressure values. The feedback controller is a proportional-integral type, and it estimates the valve aerodynamic gain from the valve area versus stroke equations.
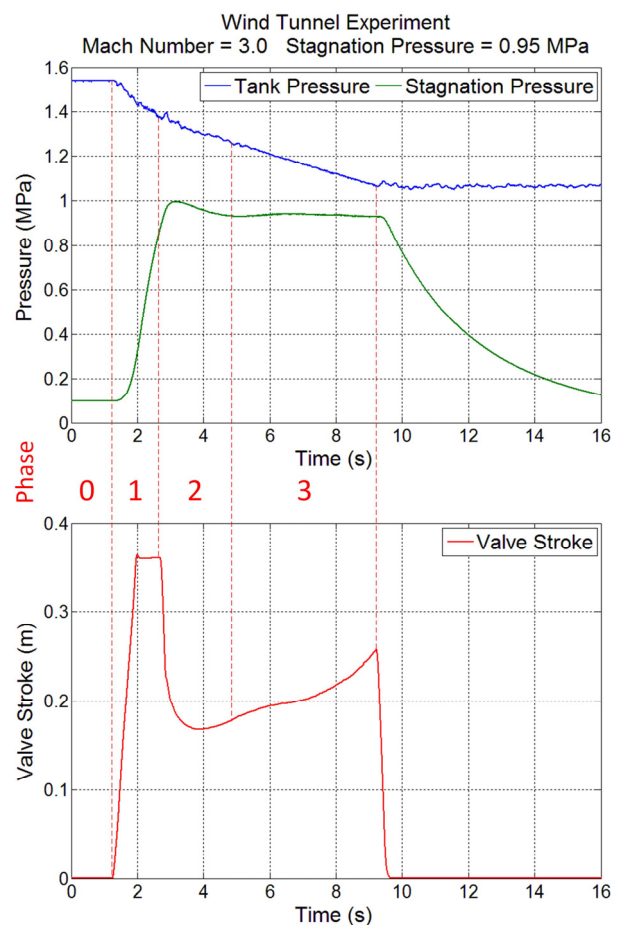

Figure 3. Wind tunnel experiment at Mach number 3.0 for the desired stagnation pressure 0.95 MPa.

The algorithm to attain and sustain the required stagnation pressure in the T-38 wind tunnel is complex and difficult to tune for different operating conditions. This is particularly true when the wind tunnel is configured to give long time constants, corresponding to the low mass flow conditions at high Mach numbers. The higher is Mach number, the higher is a stagnation pressure needed to start the supersonic flow. The switch criterion to phase 2 (Figure 3) is set to the minimum stagnation pressure value to start the flow. In some operating conditions, the stagnation pressure needed to start the flow could be very close to the desired set point value. Consequently, as the switch to phase 2 happens at higher pressure, the pressure overshoot is always present at high Mach numbers [24]. The situation is aggravated by the finite rate at which the valve can move and the slow control algorithm update rate of 16.67 Hz. The consequence of the present control strategy is slow attainment of the set point. The required stagnation pressure control accuracy is 0.3% of the nominal value. In operating conditions in Figure 3, more than 7 seconds is needed to attain the desired stagnation pressure value.

To review the present stagnation pressure control strategy, better understand challenges encountered so far and suggest improvements, the mathematical model for the wind tunnel supersonic flow is developed and applied to the T-38 test facility.

3. MATHEMATICAL MODEL FOR THE WIND TUNNEL SUPERSONIC FLOW

The mathematical model is based on the basic lumped parameter approach [25], within which the wind tunnel is divided into sections to obtain a desired discretization. For the analysis of stagnation pressure two control volumes are selected: the storage tank and the settling chamber. It is assumed that the pressure, temperature and density distributions are uniform over the entire control volume.

3.1 Modelling of the storage tank

According to the law of the conservation of mass [26], the rate of decrease of mass in the storage tank is equal to the mass flow through the valve (Figure 2):

$$-V_{ST}\frac{d\rho_{ST}}{dt} = \dot{m}_{PRV} \qquad (1)$$

Assuming that the energy loss through the pressure regulation valve is negligibly small and applying the law of the conservation of energy [26], the internal energy change in the storage tank is equal to the enthalpy and kinetic energy flux through the valve:

$$-\frac{dU_{ST}}{dt} = \dot{m}_{PRV}h_{PRV} + \frac{1}{2}\dot{m}_{PRV}v_{PRV}^2 \qquad (2)$$

Assuming that the air flow behaves both calorically and thermally as a perfect gas [5], equation (2) becomes:

$$-\frac{d}{dt}(m_{ST}c_vT_{ST}) = \dot{m}_{ST}h_{ST} \qquad (3)$$

or:

$$-\frac{c_vV_{ST}}{R}\frac{dP_{ST}}{dt} = \dot{m}_{PRV}c_pT_{ST} \qquad (4)$$

and finally:

$$\frac{dP_{ST}}{dt} = -\frac{c_pR}{c_vV_{ST}}T_{ST}\dot{m}_{PRV} \qquad (5)$$

3.2 Modelling of the settling chamber

Air flows into the settling chamber from the pressure regulation valve connected to the storage tank, and flows out through the convergent-divergent nozzle to the test section (Figure 2). According to the law of the conservation of mass [26], mass flow into the settling chamber is equal to mass flow through the nozzle throat plus rate of mass build-up in the settling chamber:

$$V_0\frac{d\rho_0}{dt} = \dot{m}_{PRV} - \dot{m}_* \qquad (6)$$

According to the law of the conservation of energy [26], the difference between energy that enters and exits the settling chamber is equal to the increase of the settling chamber internal energy:

$$\frac{dU_0}{dt} = \dot{m}_{PRV}h_{PRV} + \frac{1}{2}\dot{m}_{PRV}v_{PRV}^2 - \dot{m}_*h_* + \frac{1}{2}\dot{m}_*v_*^2 \qquad (7)$$

Using the same transformation that was applied to (2), equation (7) becomes:

$$\frac{dP_0}{dt} = \frac{c_pR}{c_vV_0}(T_{ST}\dot{m}_{PRV} - T_0\dot{m}_*) \qquad (8)$$

2.3 Mathematical model for the wind tunnel

The expressions describing the characteristics of the supersonic air flow in the wind tunnel, obtained from the preceding analysis, are the following:

$$\frac{d\rho_{ST}}{dt} = -\frac{1}{V_{ST}}\dot{m}_{PRV} \qquad (9)$$

$$\frac{dP_{ST}}{dt} = -\frac{\kappa R}{V_{ST}}T_{ST}\dot{m}_{PRV} \qquad (10)$$

$$\frac{d\rho_0}{dt} = \frac{1}{V_0}(\dot{m}_{PRV} - \dot{m}_*) \qquad (11)$$

$$\frac{dP_0}{dt} = \frac{\kappa R}{V_0}(T_{ST}\dot{m}_{PRV} - T_0\dot{m}_*) \qquad (12)$$

The mathematical model (9) - (12) is based on assumptions that there is no energy loss and that air behaves as a perfect gas [5]. However, the finite filling time of the settling chamber is taken into account by expressions (11) and (12). Even for high storage tank pressure, the settling chamber pressure will not have an appreciable rise for the first half-second to second of operation [6]. This is particularly important at high Mach numbers with low mass flow, when the wind tunnel is configured to give long time constants.

Mass flow through the pressure regulating valve is derived based on the mass continuity equation [26]:

$$\dot{m}_{PRV} = \rho_{PRV} A_{PRV} v_{PRV} \tag{13}$$

The form of equation (13) suitable for this discussion is the following [26]:

$$\dot{m}_{PRV} = \sqrt{\frac{\kappa}{R}} \frac{P_{ST}}{\sqrt{T_{ST}}} \frac{P_{PRV}}{P_{ST}} A_{PRV} \cdot$$
$$\cdot M_{PRV} \sqrt{1 + \frac{\kappa-1}{2} M_{PRV}^2} \tag{14}$$

Using isentropic compressible flow equations [26], the final expression for mass flow through the pressure regulating valve is obtained:

$$\dot{m}_{PRV} = \sqrt{\frac{2\kappa}{R(\kappa-1)}} \frac{P_{ST}}{\sqrt{T_{ST}}} A_{PRV} \cdot$$
$$\cdot \left(\frac{P_{PRV}}{P_{ST}}\right)^{\frac{1}{\kappa}} \sqrt{1 - \left(\frac{P_{PRV}}{P_{ST}}\right)^{\frac{\kappa-1}{\kappa}}} \tag{15}$$

Static pressure at the pressure regulating valve outlet (P_{PRV}) is usually assumed to be equal to the settling chamber stagnation pressure [5]. In other words, pressure difference across the valve is assumed to be given by $P_{ST} - P_0$. That way, the valve outlet flow is effectively treated as a jet expanding into an infinite volume, so that the total pressure loss is just the jet dynamic pressure. However, extensive experiments in the T-38 wind tunnel demonstrated that the settling chamber losses are in fact higher than dynamic pressure lost in expansion after the valve, and that additional losses through the baffles, silencer and screens (Figure 2) have to be taken into account. The total losses through the settling chamber are included in the model using the pressure loss coefficient (K):

$$K = \frac{P_{ST} - P_0}{P_{ST} - P_{PRV}} \tag{16}$$

In terms of the present nomenclature, K must be greater than 1. Furthermore, it must increase during a wind tunnel run since at constant stagnation pressure conditions are constant downstream of the valve, but the throttling across the valve gradually decreases. Estimates of the pressure loss coefficient for the T-38 wind tunnel are available for the complete Mach number range, based on experimental data [27]. Its value varies from about 1.0 to 1.66.

Static pressure at the valve outlet in the equation (15) is calculated based on (16):

$$P_{PRV} = P_{ST} \left[1 + \frac{1}{K}\left(\frac{P_0}{P_{ST}} - 1\right)\right] \tag{17}$$

The value of K determines the point at which the valve becomes unchocked. Both chocked and unchocked flow across the valve are included in the mathematical model (9) - (12).

The effective valve area (A_{PRV}) versus stroke is calculated based on the valve geometry and the experimentally obtained values of the valve discharge coefficient versus stroke [27] [28].

The common issue noticed in available models of supersonic blowdown wind tunnels is not taking into account the valve dynamics [6]. The rate at which the hydraulically driven valve can move is included in the mathematical model presented in this paper.

Mass flow through the nozzle throat is included in the model assuming chocked flow conditions [26], since they are achieved soon after the beginning of a high Mach number wind tunnel experiment:

$$\dot{m}_* = \sqrt{\frac{\kappa}{R}}\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{2(\kappa-1)}} A_* \frac{P_0}{\sqrt{T_{ST}}} \tag{18}$$

In supersonic flow, the nozzle throat area is well defined and it is given by [26]:

$$A_* = A_{TS} M_{TS} \left(\frac{5 + M_{TS}^2}{6}\right)^{-3} \tag{19}$$

Equations (9) – (12), representing the mathematical model of the supersonic flow in a wind tunnel, become first order nonlinear ordinary differential equations after expressing temperature as a function of pressure and density using the perfect gas equation. There are four state variables: ρ_{ST}, P_{ST}, ρ_0 and P_0. The inputs to the model are: test section Mach number (M_{TS}), which defines nozzle geometry, and valve position defined by the stroke, which uniquely determines the valve effective area (A_{PRV}) [28]. The output of the model is stagnation pressure (P_0). The system of equations (9) – (12) is numerically solved using the standard fixed-time-step finite difference technique based on the forward Euler method [29], implemented in Matlab.

3.3 Verification of the mathematical model

In order to evaluate accuracy of the suggested mathematical model, simulation and experimental results for the stagnation pressure and tank pressure versus time are compared in Figure 4. Control input to the model is the pressure regulation valve stroke profile recorded during the actual wind tunnel run at Mach number 3 and stagnation pressure 0.95 MPa (Figure 3). The initial storage tank pressure in simulation was also matched to the wind tunnel experiment used in this comparison, as well as the fixed time step of 0.06 s, corresponding to the wind tunnel control algorithm update rate of 16.67 Hz.

Figure 4 demonstrates accurate prediction of the wind tunnel response in supersonic flow conditions by the mathematical model, with relative deviation between experimental data and model results for stagnation pressure less than 1%. Experimental and simulated data for stagnation pressure increase immediately after the pressure regulating valve opening are well-matched, proving that the settling chamber volume and the effective valve area versus stroke [28] are properly taken into account in the model. Experimental and simulated stagnation pressure after the start-up phase show good consideration of unchocked and chocked flow cases, demonstrating the accuracy of the settling chamber pressure losses data [27] that are included in the mathematical model. The model

accuracy could also be attributed to the well-defined throat area in a supersonic wind tunnel.

Comparison of the wind tunnel experimental and simulated responses to control inputs indicated that the unsatisfactory stagnation pressure control was not a result of the potential wind tunnel design omissions, but the poor choice of control inputs. A modified control strategy was expected to bring improvements. However, with the existing hardware and software platform [30] and slow control algorithm update rate of 16.67 Hz, efforts have to be concentrated to the feedforward component of the control strategy, present in the all four control phases discussed in Section 2.2.
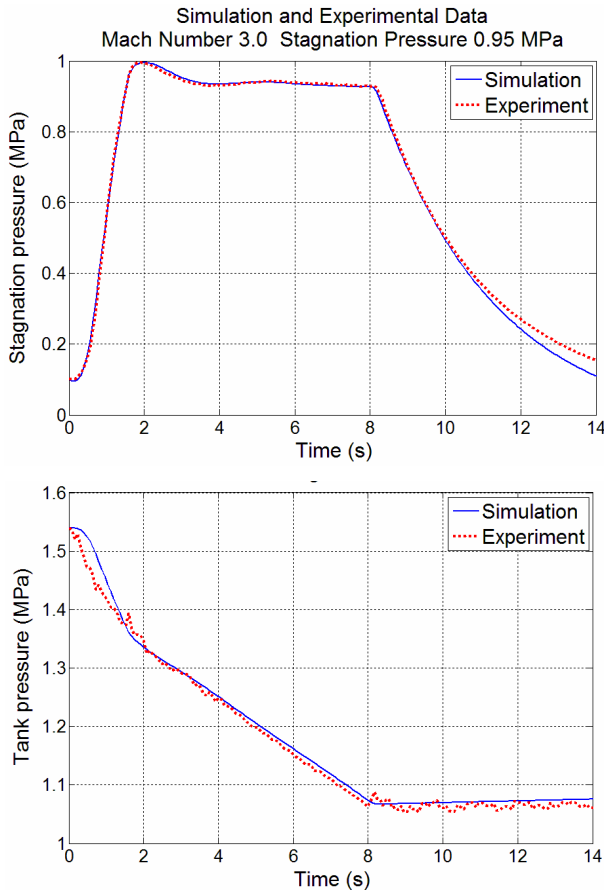

Figure 4. Simulation and experimental data for stagnation pressure (up) and tank pressure (down) at Mach number 3.0 for the desired stagnation pressure 0.95 MPa.

Since the existing control strategy is complex and with many influential parameters, the mathematical model (9) - (12) is planned to be used in numerical simulations to analyse facility response in different control scenarios, to avoid control algorithm tuning in costly wind tunnel experiments. The aim is to achieve better compromise between start-up time and smooth start of a wind tunnel test. Existing approach (Figure 3) ensured fast establishment of supersonic flow, but at the expense of reduced testing time, because of the time required to stabilize the stagnation pressure after overshoot, especially at high Mach numbers. It is hoped that better control strategy could be devised and applied to the T-38 wind tunnel, in order to bring decrease of flow stabilization time and hence, an important increase of available measurement time and improvement of the facility overall operation efficiency.

4. THE T-38 WIND TUNNEL CONTROL STRATEGY ANALYSIS AND IMPROVEMENT

The mathematical model is used to analyse the slow attainment of the required stagnation pressure at high Mach numbers in the T-38 wind tunnel. As can be seen in Figure 5, simulated mass flow variation through the pressure regulating valve and nozzle throat for the duration of the wind tunnel run presented in Figure 3 is shown. According to the control strategy, switch to the feedback control should happen when steady flow conditions are attained. However, Figure 5 clearly demonstrates that feedback control starts when the valve mass flow still oscillates around the nozzle throat mass flow value. Slow control algorithm with update rate of 16.67 Hz is not capable to trim out deviations from the set point value and achieve good regulation in such conditions.
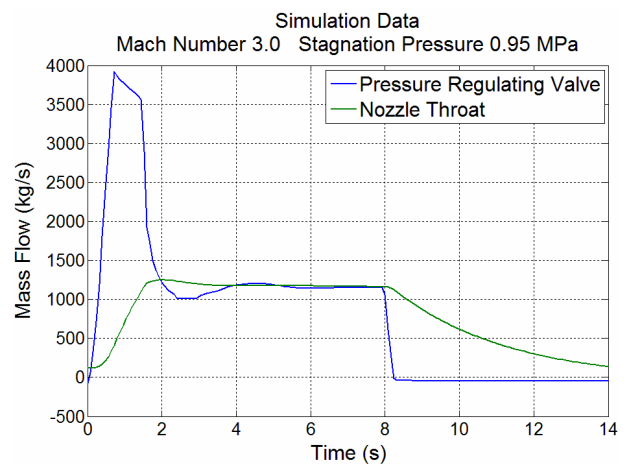

Figure 5. Mass flow through the pressure regulating valve and nozzle throat at Mach number 3.0 for the desired stagnation pressure 0.95 MPa

A smooth start of the wind tunnel, without pressure overshoot, is expected to give better results with the existing wind tunnel control system hardware and software platform. However, it could be hard to achieve because of high stagnation pressure needed to start the supersonic flow. The mathematical model (9) - (12) is numerically solved for different combinations of operating conditions in order to find the best compromise between fast and smooth start of the wind tunnel. The most critical operating conditions happen at a minimum value of the stagnation pressure for a corresponding Mach number, defined by the T-38 wind tunnel operating envelope [20]. These minimum values are very close to the stagnation pressure needed to start the supersonic flow.

The numerical simulation results for the minimum stagnation pressure 0.57 MPa at Mach number 3.0 in the T-38 wind tunnel are presented (Figure 6). The minimum stagnation pressure needed to start the flow in these conditions is 0.5 MPa [20]. According to the simulation, the slower wind tunnel start, with lower initial valve strokes, actually brings the faster attainment of the desired stagnation pressure, because of significant decrease of flow stabilization time. As a consequence of this, available measurement time is significantly increased.
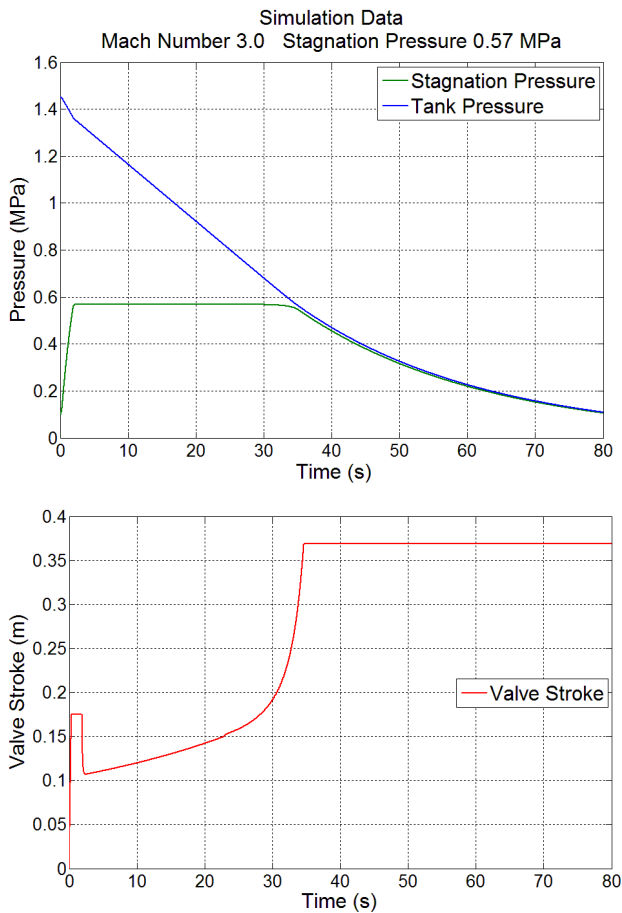
Figure 6. Simulation of the wind tunnel experiment at Mach number 3.0 for the desired stagnation pressure 0.57 MPa.

Simulated mass flow variation through the pressure regulating valve and nozzle throat is shown in Figure 7. Feedback control starts when the flow is stabilized close to the set point condition, and steady state pressure control is within required accuracy limits in about 2 seconds after the valve was opened.
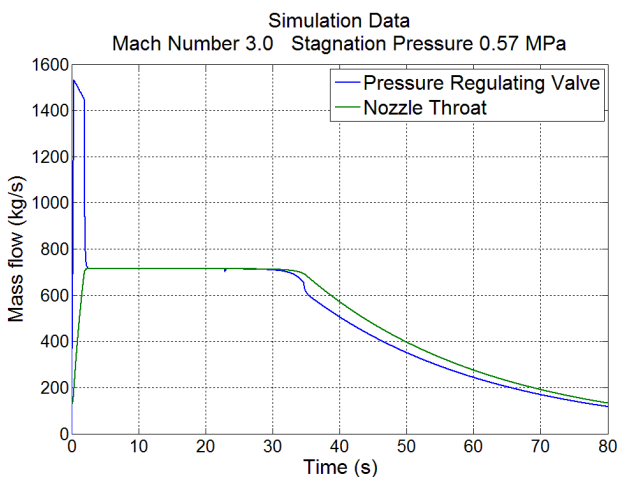

Figure 7. Mass flow through the pressure regulating valve and nozzle throat at Mach number 3.0 for the desired stagnation pressure 0.57 MPa.

Simulation results are confirmed in the actual wind tunnel experiments with the modified feedforward control. The wind tunnel experiment realized under the same initial conditions as the previous simulation (Figure 6) is presented in Figure 8.
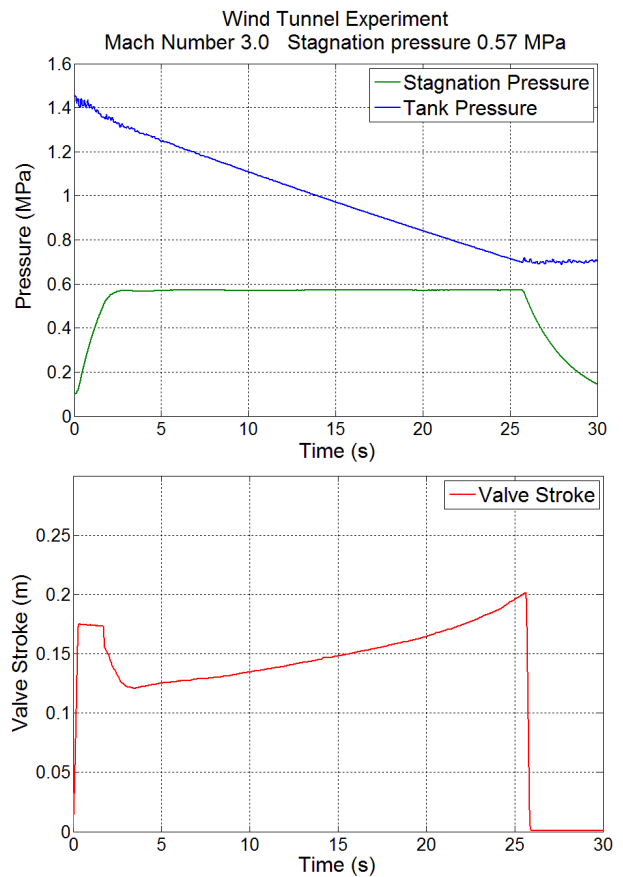

Figure 8. The wind tunnel experiment at Mach number 3.0 for the desired stagnation pressure 0.57 MPa

Comparison of results presented in Figure 6 and Figure 8 shows good match of experimental data with the model predictions. In addition, the modified feedforward control eliminates stagnation pressure overshoot and significantly decreases flow stabilization time, up to several seconds comparing to the original control strategy (Figure 3). Consequently, available measurement time is increased, as well as the overall wind tunnel operation efficiency.

5. CONCLUSION

The mathematical model proposed in this paper has been verified as a viable tool for predicting a wind tunnel response in the supersonic operating conditions. The model was used to predict the required facility setup, incorporate feed-forward control and augment an existing proportional-integral type wind tunnel control system.

In addition to traditional feedforward application, the mathematical model is planned to be used to identify the optimum control strategy based on the new hardware and software platform in the T-38 wind tunnel. In this respect, the model should be expanded and verified also for the subsonic flow conditions, which is the task that brings completely different challenges compared to the supersonic flow.

The model is also expected to serve a variety of other purposes, such as offline tuning of facility control loops, training of wind tunnel operators or facilitating wind tunnel design efforts.

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NOMENCLATURE

A_*	nozzle throat cross-section area
A_{PRV}	pressure regulating valve outlet cross-section effective area
A_{TS}	test section cross-section area
c_P	air specific heat at constant pressure
c_V	air specific heat at constant volume
h_*	enthalpy at the nozzle throat
h_{PRV}	enthalpy at the pressure regulating valve outlet
h_{ST}	storage tank enthalpy
K	pressure loss coefficient, defined by Eq. 16
M_{PRV}	Mach number at the pressure regulating valve outlet
M_{TS}	Mach number in the test section
m_{ST}	mass of the air in the storage tank
$\dot{m}_{PRV}$	mass flow at the pressure regulating valve outlet
$\dot{m}_{ST}$	mass flow at the storage tank outlet
P_0	stagnation pressure, pressure at the settling chamber outlet
P_{PRV}	static pressure at the pressure regulating valve outlet
P_{ST}	storage tank pressure
R	air gas constant
T_0	stagnation temperature, temperature at the settling chamber outlet
T_{ST}	storage tank temperature
U_0	settling chamber internal energy
U_{ST}	storage tank internal energy
V_0	settling chamber volume
V_{ST}	storage tank volume
v_{PRV}	flow speed at the pressure regulating valve outlet
v_*	flow speed at the nozzle throat
κ	ratio of specific heats
ρ_0	settling chamber air density
ρ_{PRV}	air density at the pressure regulating valve outlet
ρ_{ST}	storage tank air density

УПРАВЉАЊЕ ЗАУСТАВНИМ ПРИТИСКОМ У СУПЕРСОНИЧНИМ АЕРОТУНЕЛИМА ЗАСНОВАНО НА МОДЕЛУ

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Управљање параметрима струјања у аеротунелима је област интензивног истраживања последњих година, са циљем побољшања квалитета и ефикасности рада аеротунелских инсталација. Овај рад представља покушај да се допринесе бољем разумевању управљања зауставним притиском у суперсоничним инсталацијама прекидног дејства. Размотрена је стратегија управљања зауставним притиском у аеротунелу Т-38 Војнотехничког института у Београду. Побољшани математички модел суперсоничних аеротунелских инсталација је предложен и примењен на аеротунел Т-38. Тачност са којом математички модел предвиђа одзив инсталације у условима суперсоничног струјања демонстрирана је поређењем података из симулација и експеримената. Математички модел је употребљен за увођење измењеног алгоритма управљања у полазни управљачки систем аеротунела Т-38. Аеротунелски експерименти су потврдили предвиђања модела у погледу смањења времена успостављања струјања и повећања расположивог времена за мерење, чиме је постигнуто значајно побољшање ефикасности рада аеротунела.