Journal of Aerospace Technology and Management
ISSN: 1948-9648
secretary@jatm.com.br
Instituto de Aeronáutica e Espaço
Brasil

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Journal of Aerospace Technology and Management, vol. 1, núm. 1, enero-junio, 2009, pp. 69-77
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Control of Reynolds number in a high speed wind tunnel

Abstract: A conceptual control model for the Reynolds number test based on isentropic relations was established for the supersonic wind tunnel. Comparison of the system response of the model simulation and the actual wind tunnel test data was made to design the control system. Two controllers were defined: the first one was based on the stagnation pressure at the settling chamber; the second was based on the relation between stagnation pressure and temperature at the settling chamber which represents the Reynolds number specified for the test. A SIMULINK® block diagram code was used to solve the mathematical model consisting of mass and energy conservation equations. Performance of the supersonic wind tunnel using a PI (proportional-plus-integral) controller was found to be satisfactory, as confirmed by the results.
Key Words: *Blowdown wind tunnel, Pressure control, Mach number control, Reynolds number control.*

LIST OF SYMBOLS

A	Cross section Area	m²
C_D	Discharge coefficient	s/m
C_g	Gas sizing coefficient	-
C_p	Specific heat (constant pressure)	J/kgK
C_v	Specific heat (constant volume)	J/kgK
D	Test section diameter	m
$E(s)$	Error	Pa
h	Specific Enthalpy	J/kg
K_i	Integral controller gain	-
K_p	Proportional controller gain	-
M	Mach number	-
$\dot{m}$	Mass flow	kg/s
P	Pressure	Pa
r	Recovery factor	-
Re	Reynolds number	-
SWT	Supersonic Wind Tunnel	-
t	Time	s
T	Stagnation Temperature	K
U	Internal energy	J
v	Velocity	m/s
V	Volume	M³
θ	Valve opening position	deg
ρ	Density	kg/m³
γ	Specific heat ratio	-
μ	Viscosity	kg/s
τ	Static Temperature	K
Subscript		
1	In front of shock	
d	Desired condition	
dif	Diffuser	
exit	Exit of diffuser	
0	Settling chamber	
t	Throat of nozzle	
T	Storage tank	
TS	Test section	
v	Valve	

Received: 23/03/09
Accepted: 20/05/09

INTRODUCTION

There are many parameters that characterize a blowdown Supersonic Wind Tunnel (SWT) such as the test section dimensions, operating characteristics (Reynolds number x Mach number), general capabilities of the facility (Mach number range, maximum stagnation pressure) and so on. Many types of tests simulated in a high-speed wind tunnel are sensitive in various degrees to the errors in Mach and Reynolds number. For example, one standard task certainly is the measurement of aerodynamic forces and moments. In this kind of test, the formation of shock waves inside the test section is expected due to the presence of the model. These waves can reflect off the walls, and may cause a detrimental effect on the measurement of forces and pressures on the tested model. Since the angle of reflection is related to the Mach number (Pope and Goin, 1965), the choice of model size is a function of the Mach number in the test section.

Another restriction is the duration of the tests (run time). At a given Mach number, it is sometimes required to maximize the test duration by running the tunnel at the lowest possible stagnation pressure but still maintaining supersonic flow conditions. However, it is important to consider the undesirable variation of Reynolds number in the test section during a run. Therefore, the best choice for the stagnation pressure and temperature at a given Mach number cannot be the best choice for the Reynolds number. Due to the conflicting interrelation between these parameters it is very difficult to reproduce to estimate, theoretically, the best test configuration experimentally in aeronautical components. So, it is important (stagnation pressure, geometrical configuration of nozzles and diffuser) before each experimental test run.

In this context, a non-linear mathematical model was developed to analyze the open-loop system characteristics as well as for the controller design. The model for SWT was based on the mathematical model proposed by Fung (1987). Each module of SWT is formulated as an isentropic subsystem.

The principal difference between this work and that proposed by Fung (1987) is that, in the present work, the Reynolds number specified for the test run is controlled. A SIMULINK® block diagram code was used to solve a mathematical model consisting of a set of ordinary differential and algebraic equations derived from the mass and energy conservation. The performance of the supersonic wind tunnel using a PI (proportional-plus-integral) controller was found to be satisfactory, as confirmed by the results.

MATHEMATICAL FORMULATION

The dynamic analysis of the control system for SWT is divided into five modules: storage tank, settling chamber nozzle, test section and diffuser, Fig. 1. Control volumes mathematically represent these modules. It is important to stress here that, in the analyses to follow, isentropic relations are assumed (no shock waves, friction and heat transfer are neglected). The change of potential energy of the gas is small and can be ignored.

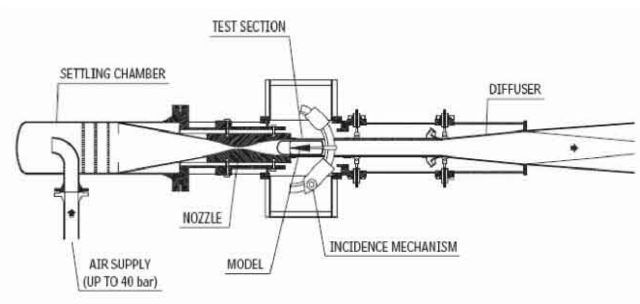


Figure 1: Blowdown Wind Tunnel (Matsumoto et al., 2001)

Storage Tank

During a test, it is assumed that the mass influx from the compressor is negligible. Hence, the rate of decrease of mass in the air tank is equal to the rate of mass efflux through the valve:

$$\frac{d\rho_T}{dt} = -\frac{1}{V_T}\dot{m}_v \tag{1}$$

where ρ_T is the storage tank air density, $\dot{m}_v$ is the mass efflux through the valve V_T and is the storage tank volume. The subscript "T" refers to the storage tank. By assuming the energy loss through the valve is negligibly small, the internal energy change in the storage tank is equal to the enthalpy plus the kinetic energy through the valve. Therefore:

$$\frac{dU_T}{dt} = -\dot{m}_v h_v - \frac{1}{2}\dot{m}_v v_v^2 \tag{2}$$

where U_T is the storage tank air internal energy, h_v is the specific enthalpy of the air through the valve and v_v is the velocity of the air through the valve. In terms of the stagnation pressure, Eq. (2) can be written (Fung, 1987):

$$\frac{dP_T}{dt} = -\left(\frac{\gamma R T_T}{V_T}\right)\dot{m}_v \tag{3}$$

The quotient $\gamma = c_p/c_v$ is the specific heat ratio and R is the gas constant. The valve characteristics are described in Fisher Controls Company (1984), by the manufacturer. The mass flow at different valve positions is given by:

$$\dot{m}_v = \frac{2.295810^{-8}}{\sqrt{T_T}} C_g P_T \sin\left(2.71\sqrt{\frac{\Delta P}{P_T}}\right) \tag{4}$$

where C_g is the "gas sizing coefficient". Note that, $C_g = C_g(\theta)$, where θ is the valve opening position. The variables P_T and P_T are the thermodynamic properties (temperature and pressure) of the air into the storage tank. ΔP is the pressure difference across the valve. It is assumed that $\Delta P = P_T - P_0$, where P_0 is the stagnation pressure at the settling chamber.

Settling Chamber

The second control volume is the settling chamber. Air flows into the settling chamber from the control valve and goes through the convergent-divergent nozzle to the test section. The energy entering the settling chamber volume with mass flow $\dot{m}_v$ minus the energy exiting through the nozzle with mass flow $\dot{m}_v$ is equal to the internal energy rate in the settling chamber. Therefore, the relation of energy conservation for the settling chamber is:

$$\frac{dU_0}{dt} = \dot{m}_v h_v + \frac{1}{2}\dot{m}_v v_v^2 - \dot{m}_t h_t - \frac{1}{2}\dot{m}_t v_t^2 \tag{5}$$

Subscript "0" refers to the settling chamber and subscript "t" refers to the throat nozzle. Rewriting the Eq.(5) in terms of stagnation pressure, results in (Fung, 1987):

$$\frac{dP_0}{dt} = \left(\frac{c_p}{c_v}\frac{R}{V_0}\right)\left(\dot{m}_v T_T - \dot{m}_t T_0\right) \tag{6}$$

The flow is without heat transfer. In this context, it is possible to rewrite Eq.(6):

$$\frac{dP_0}{dt} = \left(\frac{\gamma R T_T}{V_0}\right)\left(\dot{m}_v - \dot{m}_t\right) \tag{7}$$

since $T_0 = T_T$.

Nozzle

The nozzle of the supersonic wind tunnel is axisymmetric, variable-geometry with converging-diverging geometry. It is assumed that the flow from the settling chamber to the test section runs an isentropic process. Considering the air as a perfect gas and the stagnation state as the reference state, $\dot{m}_t$ can be written as function of stagnation pressure and the nozzle throat area A_t . The maximum flow through the nozzle will be:

$$\dot{m}_t = P_0 A_t C_D \tag{8}$$

where C_D is the discharge coefficient of the nozzle, given as:

$$C_D = \left(\frac{\gamma}{RT_T}\right)^{\frac{1}{2}}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{9}$$

The critical area A_t is function of the Mach number (M) desired in the test section and of its transversal section A, namely (Kuethe, 1998):

$$\frac{A_t}{A} = M\left[\frac{1+\left(\frac{\gamma-1}{2}\right)M^2}{\left(\frac{\gamma+1}{2}\right)}\right]^{\frac{(\gamma+1)}{[2(\gamma-1)]}} \tag{10}$$

Mach number at the Test Section and Diffuser

The Mach number at the test section is obtained from Eq.(10). With the geometrical conditions at the test section a critical area is defined considering the Mach number required by the test.

Shocks wave are the mechanism by which most supersonic flows, including those in a wind tunnel, are slowed down. When a supersonic flow passes through a shock wave, a loss in total pressure occurs. In this context, the design of most supersonic wind tunnels includes a diffuser having a converging section; a minimum cross section zone termed the "second throat" and then a diverging section. The purpose of this design is that the flow leaving the wind tunnel test section will be compressed and slowed down in the converging section of the diffuser, will pass through the second throat at a speed considerably below that of the test section, will begin to speed back up in the diverging portion of the diffuser, and will establish a normal shock in the diverging portion of the diffuser at a Mach number considerably below the test section Mach number, and with a correspondingly smaller loss. The design of the second throat provides the required position of shock wave at the divergent portion of nozzle. In order to estimate the run time, the movement of the shock wave at the diffuser is considered. The test run simulation is analyzed while the shock wave position is greater than the second throat position.

The shock position is obtained from the pressure ratio and area relation. The Mach number at the exit diffuser is given by:

$$M_{exit}^2 = -\frac{1}{\gamma-1} + \sqrt{\left(\frac{1}{\gamma-1}\right)^2 + \left(\frac{2}{\gamma-1}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left(\frac{P_0}{P_{exit}}\right)^2\left(\frac{A_t}{A_{exit}}\right)^2} \tag{11}$$

Where P_0 is the stagnation pressure at the test section and P_{exit} is the static pressure at the exit of diffuser. $P_{exit} = P_{atm}$ is adopted. The next step is to use M_{exit} to determine P_{exit}/P_{after_shock} (at the diffuser) from the isentropic relations. Since $M_{exit} < 1$, it is possible to obtain the jump relation:

$$\frac{P_0^{after\_shock}}{P_0} = \frac{P_{exit}}{P_0}\frac{P_{after\_shock}}{P_{exit}} \quad (12$$

From Eq. (12) the Mach number before the shock is calculated (M_1) using the jump relations derived for normal shock waves. With M_1, the area relation and, consequently, the shock position are calculated.

CONTROL PROBLEM

The primary reason for installing a good controller for a wind tunnel is to significantly improve flow quality in the test section. The required flow steadiness may vary with the type of tunnel. For a typical airplane test, criteria such as less than 1.0 per cent of error in Cd and Cp are usually sufficient. To meet these criteria, the Mach number steadiness in the test section must stay close to ± 0.3 per cent at $M = 3.0$ (Marvin, 1987). This control can be obtained in different ways. The first option is to control just the stagnation pressure of the settling chamber in order to keep the nozzle throat (A_t) chocked at the design conditions. Another option is to control the Reynolds number specified for the test section.

The present pressure control problem is relatively simple where only accuracy and stability are matters of prime concern. In this case it was judged that the complexities of optimal control, neural networks and so on, are neither necessary nor desirable for the present purposes.

Stagnation Pressure in Storage Tank

The objective in setting up the controller parameters for the valve is to minimize the initial transient duration to obtain as long a steady run time as possible. The control process needs a model of the pressure transmitter, the digital valve controller and the automatic ball valve to perform the SWT's control. The stagnation pressure is converted to current signal by a pressure transmitter located upstream from the nozzle. Then this signal feeds the digital valve controller. The controller has two parameters that can be changed to maintain a steady settling pressure, a proportional gain (K_p) and an integral gain (K_i). The complete description of the methodology used to determine the controller gains and the required performance index can be found in Fung et al. (1988).

The digital valve controller compares the stagnation pressure with a set pressure and derives a corrective output signal according to the setting of these two parameters. These parameters may be modified to increase the process performance. Typically, the transfer function of the PI controller is:

$$G(s)=\frac{\theta(s)}{E(s)}=K_p\left(1+\frac{1}{K_i s}\right) \tag{13}$$

where $\theta(s)$ is the valve opening position and $E(s)=P_0^{setpoint}-\frac{P_0(s)}{P_0^{Design}(s)}$ is the error signal between the reference input $P_0^{setpoint}=1$ (desired stagnation pressure at the settling chamber), and the output of the system $\frac{P_0(s)}{P_0^{Design}(s)}$ which represents the actual pressure measured. Applying the inverse Laplace transform, the differential relationship between the input and output $\theta(t)$ of the PI controller is:

$$\frac{d\theta(t)}{dt}= -K_p\frac{d\left(\frac{P_0(t)}{P_0^{Design}(t)}\right)}{dt}+\frac{K_p}{K_i}\left(P_0^{setpoint}-\frac{P_0(t)}{P_0^{Design}(t)}\right) \tag{14}$$

Reynolds number at the test section

From the preceding discussion, it is possible to control the test section condition through the control of the stagnation pressure at the settling chamber. However, during the evacuation process of air from the supply tank the stagnation temperature is not constant; moreover, this variation changes the Reynolds number significantly at the test section. In this context, a PI control system was devised based on the Reynolds number defined for the experiment. By definition, in an isentropic process:

$$\frac{P_0}{p_0}=\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}}=F^{\frac{\gamma}{\gamma-1}}$$
$$\frac{T_0}{\tau_0}=F \tag{15}$$

So, the density can be evaluated from the relations (15):

$$\rho_0=\frac{P_0}{RT_0F^{\frac{1}{\gamma-1}}} \tag{16}$$

Since:

$$\mathrm{Re}=\left(\frac{\rho v D}{\mu}\right)_0 \tag{17}$$

it is possible to write:

$$\mathrm{Re}=\left(\frac{\rho DM\sqrt{\frac{\gamma P}{\rho}}}{\mu}\right)_0=\frac{\rho_0 DMF^{\frac{\gamma+1}{2(\gamma-1)}}\sqrt{\gamma RT_0}}{\mu_0} \tag{18}$$

Using the definitions:

$$A=\frac{\pi D^2}{4} \quad \text{and}$$
$$\rho_0\sqrt{\gamma RT_0}=\frac{P_0}{F^{\frac{1}{\gamma-1}}}\sqrt{\frac{\gamma P_0}{RT_0}} \tag{19}$$

The Reynolds number can be written as a function of stagnation conditions of the flow:

$$\mathrm{Re}=\xi\frac{P_0^{1.5}}{T_0} \tag{20}$$

Where the constant ξ is given by:

$$\xi = \frac{\xi_2}{\xi_1} F \text{, and:}$$

$$\xi_1 = 2.3110x10^{-08} \tag{21}$$

$$\xi_2 = \sqrt{\frac{4\gamma A M^2}{\pi R}}$$

Viscosity is defined by:

$$\mu = 2.3110x10^{-08}\sqrt{T_0} \tag{22}$$

The set point condition was defined in function of Reynolds number designed for the experiment, which is:

$$\mathrm{Re}_{Setpoint} = 1 \tag{23}$$

Finally, the controller equation which must be applied to the plant is:

$$\frac{d\theta(t)}{dt} = -K_p \frac{d\left(\frac{\mathrm{Re}(t)}{\mathrm{Re}^{Design}}\right)}{dt} + \frac{K_p}{K_i}\left(\mathrm{Re}^{Setpoint} - \frac{\mathrm{Re}(t)}{\mathrm{Re}^{Design}}\right) \tag{24}$$

NUMERICAL IMPLEMENTATION

From the preceding discussion, expressions were obtained which describe the behavior of the SWT and the control systems. These are summarized here:

Storage Tank

$$\frac{d\rho_T}{dt} = -\frac{1}{V_T}\dot{m}_v$$

$$\frac{dP_T}{dt} = -\left(\frac{\gamma R T_T}{V_T}\right)\dot{m}_v$$

Control Valve

$$\dot{m}_v = \frac{2.295810^{-8}}{\sqrt{T_T}} C_g P_T \sin\left(2.71\sqrt{\frac{\Delta P}{P_T}}\right)$$

Settling Chamber

$$\frac{dP_0}{dt} = \left(\frac{\gamma R T_T}{V_0}\right)(\dot{m}_v - \dot{m}_t)$$

Nozzle

$$\dot{m}_t = P_0 A_t \left(\frac{\gamma}{R T_T}\right)^{\frac{1}{2}} \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

Valve Angle

$$\frac{d\theta(t)}{dt} = -K_p \frac{d\left(\frac{P_0(t)}{P_0^{Design}(t)}\right)}{dt} + \frac{K_p}{K_i}\left(P_0^{setpoint} - \frac{P_0(t)}{P_0^{Design}(t)}\right)$$

Or

$$\frac{d\theta(t)}{dt} = -K_p \frac{d\left(\frac{\mathrm{Re}(t)}{\mathrm{Re}_{Design}}\right)}{dt} + \frac{K_p}{K_i}\left(1 - \frac{\mathrm{Re}(t)}{\mathrm{Re}_{Design}}\right)$$

The above equations become a system of six first-order nonlinear differential equations, in time, derived from the mass and energy conservation (Storage Tank, Settling Chamber, Nozzle), constitutive equation (gas and control valve) and control equations (Valve angle).

There are six state variables, which are: P_t, ρ_t, Po, θ, m_t and m_v. The inputs of this system are: test section Mach number, which results in a determined nozzle geometry; the valve position $\theta(C_g)$, which determines the control valve behavior, according to changes in C_g; The outputs of this system are the stagnation pressure (Po) and temperature (***To***) in the settling chamber, angle valve ($\theta(t)$), Mach and Reynolds number at the test section.

Figures 2, 3 and 4 show schematic block diagrams relating to the SWT model, making use of a graphical editor of the MATLAB-Simulink package (Mathworks, 2002).

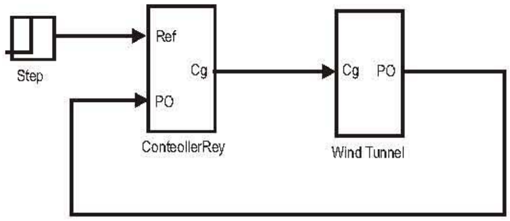


Figure 2: Block diagram: Stagnation Pressure Controller

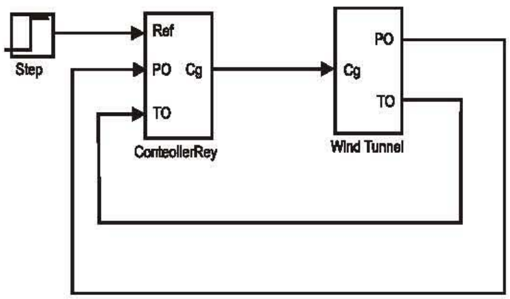


Figure 3: Block diagram: Reynolds Controller

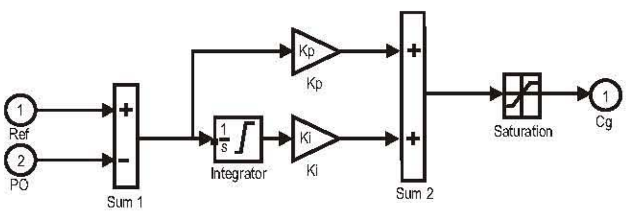


Figure 4: Block diagram: Controller Detail

RESULTS

The results are presented following the sequence below:

- Wind tunnel without controller;
- Wind tunnel with stagnation pressure control;
- Wind tunnel with Reynolds number control;
- Temperature variation;
- Shock position at the diffuser.

Wind Tunnel without Controller

Figure 5 shows a comparative picture with the plant without controller. Although the Mach number at the test section does not change during the test run (70 sec), there is a big variation in terms of Reynolds number. In this context, it is possible to conclude that Fung's wind tunnel configuration needs a control system.

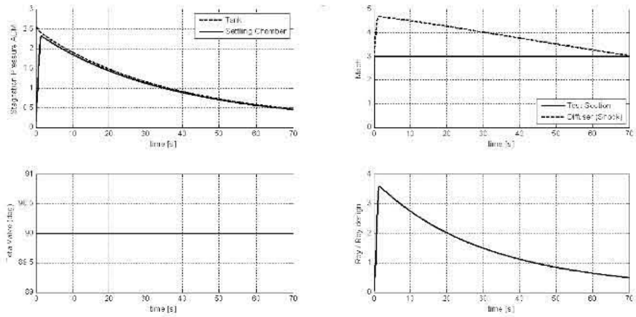


Figure 5: Wind tunnel without controller

Wind Tunnel with Stagnation Pressure Control

In order to compare the experimental results with those from the mathematical model simulation, the same conditions adopted by Fung (1987) were established for the present case. The research of Fung (1987) deals with the solution of the stagnation pressure control problem at the settling chamber in the SWT. This reference case is a good test to evaluate the concordance among different mathematical models. By adding a controller in a feedback loop to the wind tunnel plant, the mathematical model for the closed-loop system is established. The results are shown in Tab. 2.

Table 2: Comparison of results from simulation and experimental data ($P_T = 260$ psia)

Mach	P_0 [Psia]	Run Time [s] Experimental	Run Time [s] Present Work
2.5	80	55	49
3.0	110	50	45
3.5	160	40	32

It can be seen that the performance of the real wind tunnel is even better than the simulation. The reason is the assumption of an adiabatic process in the simulation. In reality, heat transfer takes place particularly through the large tank surface during the test. While the tank temperature decreases during the test, a finite amount of heat is transferred from the tank walls to the inner air. This leads to a higher tank temperature as well as a higher tank pressure than predicted by the model, Fung (1987).

Figure 6 shows the behavior of the system at Mach number 3. The results are expressed in terms of stagnation pressure and stagnation temperature at the settling chamber, stagnation pressure at the tank, Mach and Reynolds number at the test section, and the angle valve (between the tank and settling chamber). The stagnation pressure control at the settling chamber was used. It can be concluded that the control system based on the stagnation pressure at the settling chamber was found to be satisfactory, although the Reynolds number was not constant at the test section. Curiously, for this particular configuration, significant variation in angle of valve was not found.

Thus, this control would be run manually. Finally, it can be observed that the constant average controller parameters found above are effective at all Mach number (2.5 to 4.0) in obtaining a response with a minimum steady-state error and overshoot with a minimum settling time.

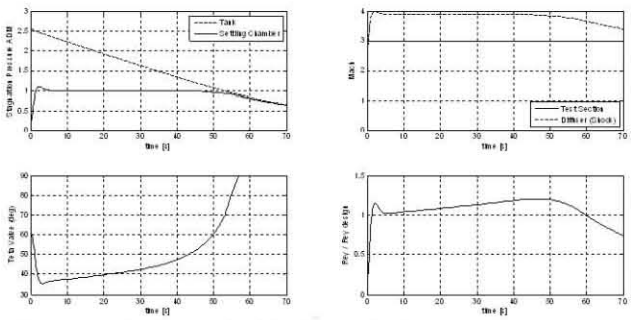


Figure 6: Wind tunnel with Stagnation Pressure control

Wind Tunnel with Reynolds number Control

Figure 7 shows the same configuration adopted in the last section but, this time, with the Reynolds number controller. The objective is to compare the results obtained for Mach and Reynolds number at the test section using both control methodologies. Although the Mach number required to run using Fung's control system is achieved, there is a considerable difference between the methods (20 per cent approximately) in terms of Reynolds number.

The principal reason for this difference is related to the temperature involved in this process. The Reynolds number controller considers the temperature variation during the transient analysis, Eq. (20), adjusting the mass ratio in a different way from the stagnation pressure control. Thus, a different angle valve variation is expected, Figs. 6 and 7. According to Pope and Goin (1965), there are two ways in which blowdown WT are customarily operated: with stagnation pressure constant or with constant mass flow. For constant mass runs the stagnation temperature must be held constant and either a heater or a thermal mass external to the tank is required. For constant stagnation pressure (settling chamber), the only control necessary is a pressure regulator that maintains the stagnation pressure constant. This report considers a relationship between stagnation pressure and $(P_0^{1,5}/T_0)_{Settling\_Chamber}$ temperature, which characterizes the Reynolds number at the test section as control parameter at the plant. Finally, it is interesting to note that this mathematical model is an attractive tool for analyzing different test configurations, which require different control methodologies.

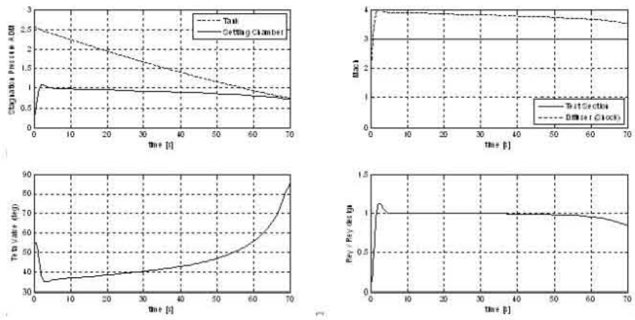
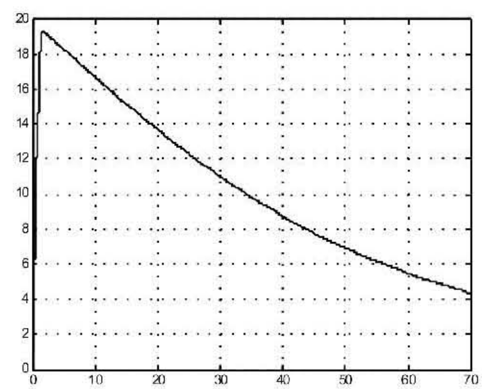


Figure 7: Wind tunnel with Reynolds number control

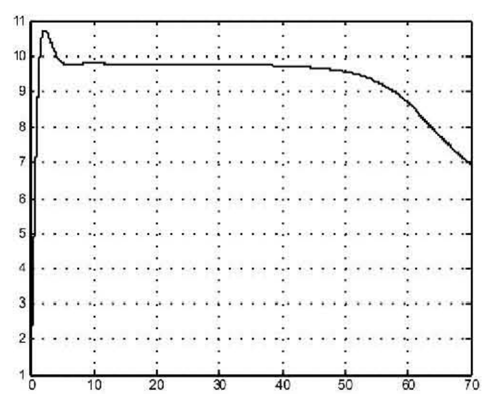
Shock Position

Figure 8 shows the results obtained using the different types of control system adopted in this report. The shock position at the diffuser is directly dependent on stagnation pressure at the settling chamber. So, a constant location is expected during the test run if a stagnation pressure controller is adopted for the plant.

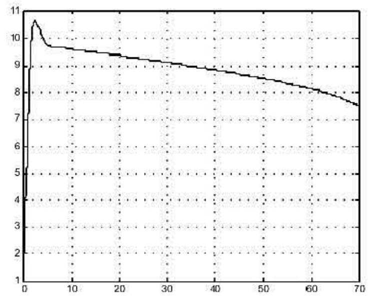
The reason for tracking the shock wave at the diffuser is to evaluate the Mach number at the test section. The test run simulation is conducted while the shock wave position is greater than the second throat position.



(a) Plant without controller



(b) Plant with stagnation pressure controller



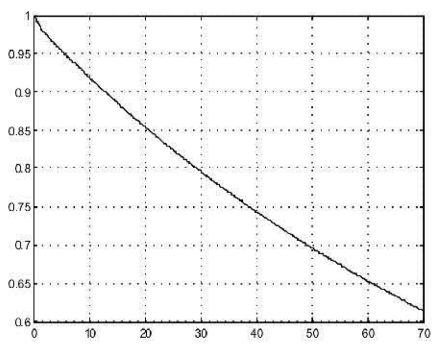
(c) Plant with Reynolds number controller

Figure 8: Shock position.

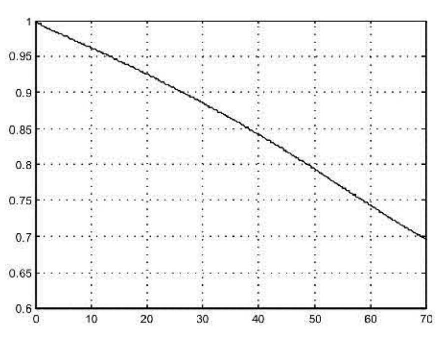
Temperature Variation during the Test

Achieving constant stagnation pressure is a critical concern for supersonic wind tunnel testing. The control algorithm is designed such that it is suitable for different Mach number testing and, at the same time, obtaining the maximum test time for different stagnation pressures.

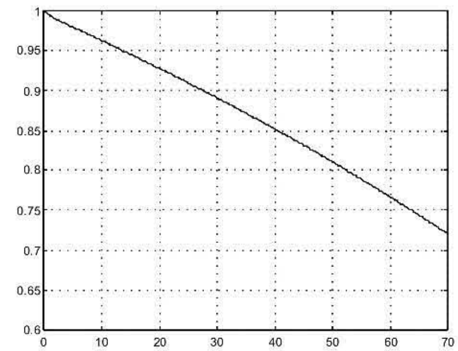
However, the temperature variation is another requirement for the experimental analysis. Since the Reynolds number is a function of stagnation pressure and temperature, it is necessary to consider the temperature variation in the control algorithm as well. Figure 9 shows the different profiles when the plant without controller is considered, with stagnation pressure control and with Reynolds number control.



(a) Plant without Controller



(b) Plant with Stagnation Pressure Controller



(c) Plant with Reynolds number Controller

Figure 9: Temperature Variation

The curve shape and the minimum value of temperature is the principal concern. From these results it is possible to conclude that the algorithm developed for the Reynolds number controller is more efficient when flow quality and test time are considered.

CONCLUSIONS

A conceptual control model, based on the Reynolds number at the test section, was established for the supersonic wind tunnel. Comparison of the system response of the model simulation and the actual wind tunnel test (Fung, 1987) data was made to determine the applicability of the model.
Two controllers were defined: the first one was based on the stagnation pressure at the settling chamber; the second was based on the relation $\left(P_0^{1,5}/T_0\right)_{Settling\_Chamber}$.

Performance of the supersonic wind tunnel under different Mach numbers and stagnation pressure was tested. The following conclusions were drawn from the results of simulations:

(i) The isentropic approach can be used for preliminary design of the control system based on stagnation pressure at the settling chamber or Reynolds number at the test section. According to the single-loop adopted in these analyses, the second option is to be preferred since it is possible to obtain Mach and Reynolds number control simultaneously. It is important to stress here that, the principal reason in adopting the control system based on the Reynolds number at the test section is not directly related to the run time. The concern is about quality of flow.

(ii) The mathematical formula applied to the normal shock wave at the diffuser can be an interesting tool to be used in analysis of run time, when the Mach number is considered as a control parameter. The cases presented in this report consider the Mach number at the diffuser greater than the Mach number at the test section. It is not a common practice. Thus, it is extremely important to analyze the stability of shock wave at the divergent portion of diffuser before defining the variable $P_0^{setpoint}$;

(iii) After investigating different control algorithms, a single-input single-output PI controller has been chosen for this task because of its simplicity and availability. The major problem in implementing this control system is the highly nonlinear relationship of both the gas dynamics and the valve-nozzle characteristics. The linearized mathematical model was used to analyze the open-loop system characteristics as well as for the controller design. However, it is interesting to improve this mathematical model implementing the gain calculator in order to provide an automated design tool for blow-down wind tunnel testing.

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