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THE FFA T1500 INJECTION DRIVEN TRANSONIC WIND TUNNEL

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Abstract

A new high Reynolds number transonic wind tunnel has been built in Sweden for the Aeronautical Research Institute (FFA). The tunnel has a closed circuit with a 1.5 m × 1.5 m test section and is injector driven from an existing 250 bar air supply system. The Mach number range is 0.3 - 1.2 with a conventional contraction and a sonic second throat and 1.4 with a convergent-divergent contraction. The stagnation pressure range is 100-550 kPa at the lowest Mach number. This range decreases for increasing Mach numbers mostly because of practical restrictions as dynamic pressure and run time limits.

Initial testing of different flow properties as Mach number distribution, flow angularity, turbulence intensity and pressure fluctuations has been performed and results are presented. The performance of the wind tunnel control system has also been checked regarding its ability to control Mach number and stagnation pressure.

Introduction

The history of the T1500 wind tunnel dates back to the beginning of the seventieth when the need for a high Reynolds number facility became obvious. Several attempts were made to raise funds for a blowdown wind tunnel but they were turned down. Consequently, during the last ten years of Swedish project oriented wind tunnel testing has been conducted abroad as our facilities were ged inferior.

Finally in 1985 funds were granted for an injection driven wind tunnel. The reason not to build a blowdown wind tunnel was that the drive and air storage system of an existing hypersonic tunnel could be used and with the high storage pressure, 25 MPa, the injection drive principle became natural.

With a 1.5 m × 1.5 m test section size the Reynolds number capability of the T1500 is about 4 times that of other existing FFA wind tunnels. In Figure 1 Reynolds number is shown at different Mach numbers and stagnation pressures. Reference length is the usual $0.1 \times \sqrt{A}$ (A is the test section cross area), in the T1500 case 0.15 m. The Mach number range is 0.3-1.2 with a conventional convergent contraction while it is possible to run M=1.4 with a convergent-divergent contraction. The stagnation pressure range is 100-550 kPa at the lowest Mach numbers. This gives a very wide operational range and makes it possible to taylor a test program for most needs.

The contract to build the tunnel was awarded to FluiDyne Engineering Corporation of Minneapolis, Minn., USA. In both design, construction and site installation Swedish subcontractors were used extensively. The wind tunnel building was managed by the Swedish National Board of Public Buildings while many other programs were run by FFA, sometimes with the help of consultants. To be mentioned here are the data acquisition system, acceptance test equipment, balances, a balance calibration rig and a schlieren system. An aerial photo of the facility is shown in Figure 2.

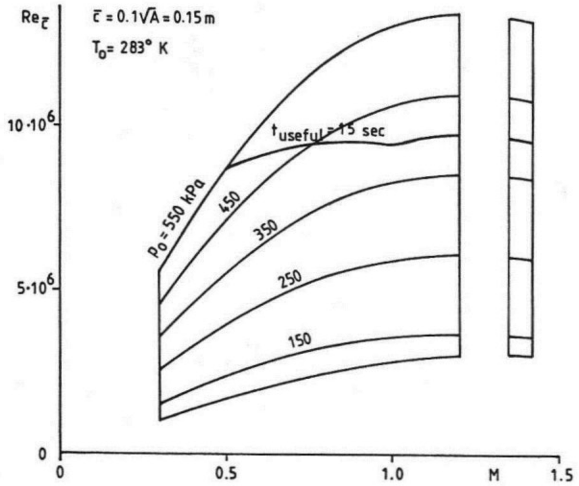


Figure 1. Reynolds number range for T1500.

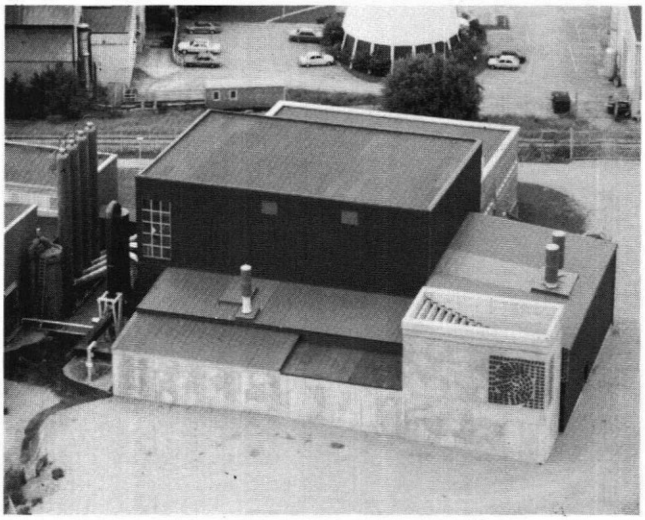


Figure 2. Aerial photo of the T1500 facility.

Main Features of the Wind Tunnel

The T1500 wind tunnel is a closed circuit wind tunnel. The total circuit length is 86.8 m of which the test and return legs are 28.8 m and the crosslegs are 14.6 m. In Figure 3 an overview of the tunnel, the air supply and the exhaust piping can be found. The complete tunnel is housed in a steel building. The test leg together with corner no. 1 and the main circuit exhaust is housed in a heated part of the building while the rest of the tunnel is indoors due to environmental noise considerations. The exhaust duct and stack is made of thick reinforced concrete and is acoustically treated for the same reason.

Air Supply System

The existing air supply system consists of two 1.1 MW electric motors, each driving a 6-stage piston compressor delivering air at 250 bars and at a rate of 1.6 kg/sec. This air is stored in 4 pressure vessels interconnected through rather narrow pipes. To connect this system to the new wind tunnel the pressure vessel manhole openings were used and a manifold was manufactured leading to a new pressure vessel with an internal thermal matrix. With this the temperature drop during a run is limited to a few degrees. The thermal matrix is reheated between runs with air from the compressors recharging the pressure vessels.

From the thermal matrix the air piping is directed into the exhaust duct where the very noisy injection control valve is located. The high pressure piping and the thermal matrix are electrically heated and insulated. This is to keep the material from becoming brittle when exhausting to low storage pressures. The manifold, thermal matrix and the air supply piping up to the injector valve have been hydrotested to 32.5 MPa.

Injector System

From the injector valve air is directed to a manifold surrounding the main tunnel tube close to downstream of corner no. 2. From this manifold there are 16 outlets going through the tunnel shell and ending into convergent-divergent nozzles. In Figure 4 there is a photo of the injectors. Typical injector pressures are in the range 600-3200 kPa and the injected mass flow rate is in the range 100-550 kg/sec. This part of the piping system is fitted with a bursting disc for safety in the event that the injector valve runs out of control. The injector pipes in the tunnel are faired to reduce losses.

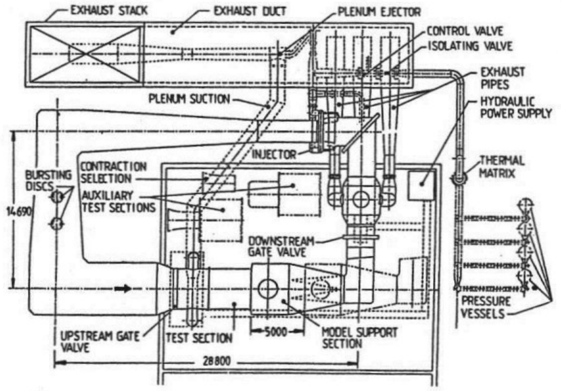


Figure 3. T1500 facility lay-out.

Pressure Shell

The complete tunnel circuit is a pressure shell which has been designed for an absolute pressure of 550 kPa. As such it has to comply with the Swedish pressure vessel code and extensive work has been done by both the wind tunnel supplier and the Swedish pressure vessel authority, SA, to assure that the design is acceptable. Fatigue was a main concern in the design phase and a conservative scheme for number of runs at different pressures and Mach numbers was defined for the life of the tunnel. As a safety device there are two burst discs on the shell between corners 3 and 4. These are designed to keep the tunnel from being overpressurized with a wide open injector valve.

The complete tunnel circuit was hydrotested to 820 kPa at the tunnels lowest point. This was successfully performed in March 1988. The load of the tunnel filled with 1000 tons of water was the design criteria for columns and foundations. A comparison between the resulting pressure shell steel sheet thicknesses whether the tunnel is designed to Swedish or American pressure vessel codes can be found in Reference 1.

Stilling Chamber and Contraction

Downstream of the injector air is mixed with tunnel circuit air and its velocity is then reduced as the air flows through a diffuser, corner no. 3, another diffuser and enters the stilling chamber through corner no. 4. This part of the tunnel has the largest diameter, 5 m. The first flow

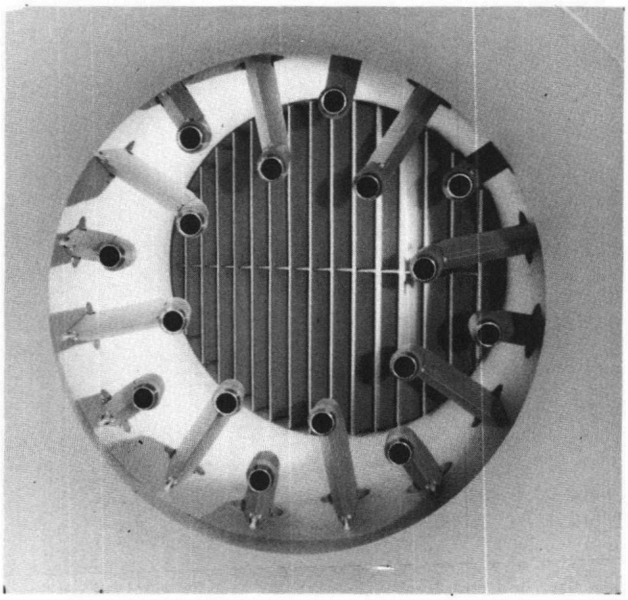


Figure 4. The injectors with corner no. 2 guide vanes in the background.

manipulation device is a set of 13 vertically oriented acoustic baffles. These are designed to keep the intense injector noise from entering the test section.

At the trailing edge of the acoustic baffles there is a honeycomb. Its cell size is 10 mm and the cells have a L/D ratio of 10. Downstream of the honeycomb there are three stainless steel screens, the upstream two are 12 mesh while the third is 24 mesh.

After the stilling chamber follows the contraction, which consists of two parts. The upstream part is integral with the stilling chamber and here is the transition from circular to a quadratic cross section located. The downstream part is mounted to the upstream flange of the test section and is interchangeable with a convergent-divergent contraction for M=1.4. Between the two contraction parts there is a gate valve. With a corresponding gate valve downstream of corner no. 1 it is possible to isolate the test leg, keep the rest of the tunnel pressurized and enter the test section. This saves valuable compressor pumping time.

Test section

The test section is 4 m long and has a square 1.5 m × 1.5 m cross section. The pressure shell surrounding it is circular with 3.6 m diameter. The plenum chamber between the pressure shell and the test section walls is connected to the plenum surrounding the rear part of the contraction. Here two large pipes are connected to the exhaust duct through two plenum exhaust valves.

The test section is configured with slotted walls, 4 in each wall. Every slot is made as a separate unit which rapidly can be removed from the tunnel. These can be exchanged for other inserts giving either a strip-perforated wall or solid wall configuration. A set of solid wall inserts have been manufactured. They are equipped with spring loaded pressure relief panels to reduce the pressure differential across the test section walls. The top and bottom walls are movable ±0.75° making it possible to get a flat Mach number distribution in the test section. Air that is sucked out of the slots is directed forward in the plenum and leaves the tunnel through the pipes at the contraction. At low tunnel pressures the plenum pressure will be below ambient and to be able to suck air out through the slots a plenum exhaust ejector, located in the exhaust duct, is used. The ejector is always run in such a way that the plenum exhaust valves are choked. The ejector is driven with air exhausted from between the injector valve and the main injector.

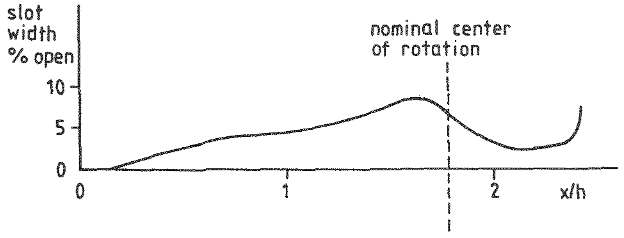


Figure 5. Test section slot shape.

The shape of the slots is quite unusual and shown in Figure 5. The shape has been designed at FFA and is a compromise as every combination of model, Mach number and angle of attack requires a set of separately designed slots to minimize wall interference. An example of earlier work in this field at FFA can be found in Reference 2.

The slots and test section walls are made of hard extruded aluminum profiles that have been anodized to get a hard surface. The permanent parts of the test section walls are equipped with some 250 pressure taps with some of these connected to electronically scanned pressure blocks installed in the plenum. The test section also has windows for a schlieren system. The inner windows can be exchanged for aluminum blanks equipped with pressure taps depending on the nature of the test.

Model Support Section

In the model support section the model support system is mounted consisting of a vertical strut and on that a sting pod. The strut moves vertically and the sting pod performs a pitching motion, both are hydraulically actuated by separate actuators. On the front face of the sting pod a roll drive is mounted and the roll drive has a female taper for a sting. The front face of the sting pod has a 10° oblique angle which results in an angle of attack range of -15° to 25° when rotating at the nominal center of rotation, which is 2670 mm downstream of the forward end of the test section. With other combinations of the vertical rate in relation to the pitch rate it is possible to have the model rotate around an arbitrary point. The maximum pitch rate with a coordinated motion is 6°/sec and the maximum allowed normal force at the nominal center of rotation with the roll drive is 26 kN. If the roll drive is substituted by a solid extention the model support system is designed for as much as 72 kN in normal force. Combinations of roll and pitch angles could be programmed to give a constant angle of sideslip with changing angle of attack. This can, however, not be run in a continuous mode, a pitch-pause mode has to be chosen.

Aft of the strut is the second throat or choke located. The choke consists of six symmetrical profiles with cut off trailing edges entering the stream tube from each sidewall. The total area of these profiles is large enough to create sonic speed in the choke while the test section Mach number is as low as 0.3. The choke will control the test section Mach number. It will also prevent injector noise from propagating upstream into the test section.

In contrast to most transonic wind tunnels the air in the test section plenum is not vented into the main stream in the model support section. The reason not to use that method was a concern for run time length at the top of the performance envelope runs. The test section plenum and model support plenum are also isolated from each other.

Main Circuit Exhaust Section

Downstream of the second throat follows a high speed diffuser and corner no. 1. In the crossleg between corners no. 1 and 2 the downstream gate valve is located followed by the main circuit exhaust section. The air first enters a plenum surrounding the stream tube and is then directed into three large exhaust pipes. In each pipe there is a butterfly valve. Downstream of the valves there is an ejector on each pipe making it possible to run at lower stagnation pressures than would otherwise have been possible. The air is then directed into the exhaust duct. Splitter plates are mounted in the pipes to get a higher noise frequency which is easier to attenuate. A flange for a fourth exhaust pipe is blinded and is planned to be used if the performance envelope will be extended to higher Mach numbers. An additional exhaust pipe together with an exhaust valve, hydraulic actuator, plumbing, integration into the control computer etc then has to be installed.

Handling Considerations

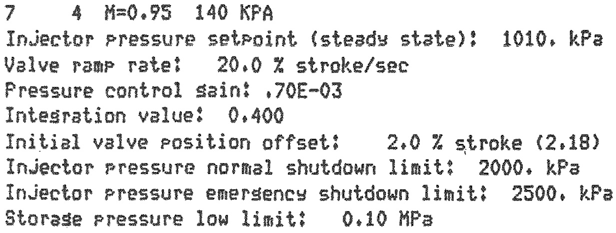
The limiting productivity factor in this tunnel is the time taken to recharge the pressure vessels between runs. For typical runs this time is about 45 min. It is important that the time between runs is used as efficiently as possible in order not to lessen the productivity for other reasons than for pressure vessel recharging. This was brought to attention early in the design of the wind tunnel and is reflected in several features.

The most obvious is the way in which the tunnel is opened and closed. The model support section, high speed diffuser and corner no. 1 is one unit and put on rails. When the tunnel is opened this part is translated away from the test section and a movable platform is inserted and raised between the two sections. A sting-mounted model is then reached from the fixed platform beside the tunnel. A technician working with the model can stand upright and do not have to walk in any stairs to reach the model. To speed up the opening of the tunnel the following steps take place with the push of just one button: the gate valves are closed, the test section is vented, the tension in the upstream and downstream disconnects is released and the pins connecting the tension rods with the model support section are pulled. Then the model support section can be translated and the movable platform inserted. This could also be part of the automatic sequence but for safety reasons this is done by a technician. This whole process takes less than five minutes.

When changing rear contractions the model support and test sections are translated together and the contraction is removed from the forward bulkhead of the test section while suspended in the wind tunnel hall overhead crane. This change takes roughly one hour. Consideraation was also given to the time allowed for the change of test section wall inserts. By releasing two nuts the clamp force of several wedges is off-loaded and one slot can be slided out and changed. Changing test section wall.configuration in this way takes also about one hour.

Wind Tunnel Control

The T1500 wind tunnel is digitally controlled with a PDP 11/83 computer. With the limited air storage and thus short run times it is important that the air is used as efficiently as possible. 50 times/sec the signals from several transducers are sampled, converted to engineering units, compared to the set points and new set points are calculated and transferred to the different actuators. A run is set-up by entering data in several menus before a run and at actual run time all sequencing is automatic although the operator has the possibility to force a shutdown. An example of one of the menus is shown in Figure 6, this one covers the set-up of the injector control. In this way the control of the tunnel is very flexible. On the other hand there is quite a lot of data that has to be entered for each run even if most data is the same from run to run. A separate program has been written to facilitate the set-up of the tunnel. This program is regularly updated to incorporate the ever increasing experience from the tunnel runs. After each run it is possible to get historical data printouts and plots.



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7     4  M=0.95  140 KPA
Injector pressure setpoint (steady state):  1010. kPa
Valve ramp rate:   20.0 % stroke/sec
Pressure control gain: .70E-03
Integration value:  0.400
Initial valve position offset:    2.0 % stroke (2.18)
Injector pressure normal shutdown limit:  2000. kPa
Injector pressure emergency shutdown limit:  2500. kPa
Storage pressure low limit:   0.10 MPa
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Figure 6. Example of a setup menu for injector control.

Injector Control

Before any running starts the tunnel is pressurized to the intended stagnation pressure of the forthcoming run. At the start of the run the injector valve is ramped open to the preset position determined by the control computer. The valve is then held fixed at the preset position for usually half a second and after that closed loop control is initiated. The control computer is then trying to keep the injector pressure as measured in one of the 16 pipes constant. Simultaneous with the opening of the injector valve the circuit exhaust valves are ramped open to a preset position where the valves are locked for 0.5 sec before closed loop control starts. The input here is the stagnation pressure as measured downstream of the screens in the stilling chamber. In this mode the stagnation pressure is controlled but the Mach number is not possible to control although the choke can be preset in any position. As the Mach number is not possible to control this is a seldomly used run mode.

Choke Control

This is the most commonly used run mode in the Mach number range 0.3 < M < 1.2. The choke is used to reach a preset Mach number and also for controlling the Mach number with a pitching model in the test section. The tunnel is started as for injector control and with the choke preset to a value corresponding to the intended Mach number. 1.0 sec after closed loop control of the main circuit exhaust valves have been initiated, closed loop control of the choke starts. The command value here is a fixed ratio between test section plenum pressure and stagnation pressure. A certain time after closed loop control is initiated the model support program is started and data sampled with the data acquisition system. An example of the sequencing of valves and the resulting pressures and Mach number is shown in Figure 7. Usually the plenum exhaust valves are ramped at the start to a preset position and held fixed throughout the run and then rapidly closed. In the event the plenum exhaust ejector and the main circuit exhaust ejector are needed they are ramped in the same way as the plenum exhaust valves.

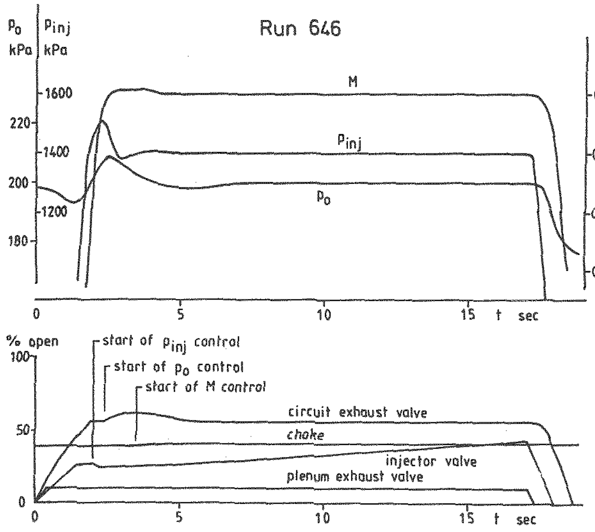


Figure 7. Example of a run in choke control mode.

Plenum Exhaust Control

The plenum exhaust control mode is similar to the choke control mode but instead of controlling with the choke fingers the plenum exhaust valves are used. This control mode can be used in the Mach number range 1.0 < M < 1.2 and with the choke fingers preset or retracted. As the slotted walls are used at M=1.4 the plenum exhaust control mode is used at this Mach number too. The choke fingers are then retracted. An example from a plenum exhaust control run at M = 1.4 is shown in Figure 8.

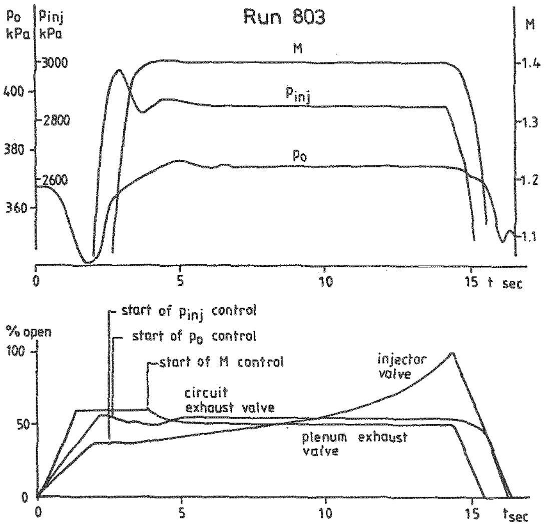


Figure 8. Example of a run in plenum exhaust control mode.

Mach Sweep Run

It is possible to make a sweep in Mach number during a run. The tunnel is started in the choke control mode but instead of starting the model support program the Mach number is ramped at a certain rate. The plenum exhaust valves are then ramped at a fixed rate between the positions needed for a flat Mach number distribution at the two end Mach numbers. To control the rate of change of Mach number the choke is used. In Figure 9 the Mach number is changed from 0.70 to 1.05. It is obvious from the figure that the change in choke position with time is not constant.

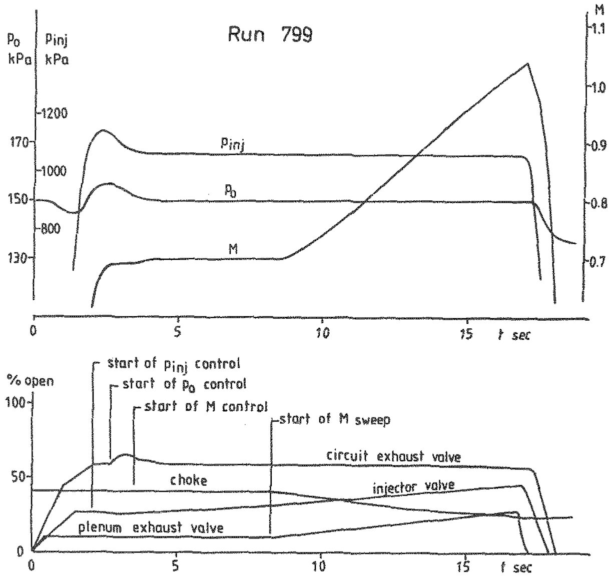


Figure 9. Example of a Mach sweep run.

Model Blockage Compensation

When the tunnel is tuned for a flat Mach number distribution in the test section the plenum flow removal and the top and bottom wall angles are adjusted. This gives a relation between the empty test section and plenum Mach numbers. When a model is installed and pitched there will be a blockage wake behind the model. In a conventional transonic tunnel this would result in an increased flow through the slots into the plenum and then to the diffuser in the model support section. In T1500, however, the plenum exhaust valves are run choked and the result will instead be an increase in velocity downstream of the model, almost as if there was a solid wall test section.

To compensate for the model blockage the following scheme in plenum exhaust valve modulation has been adopted. The equivalent freestream area of the wake can be calculated as follows:

$$A_{wake} = \frac{C_D \times S_{ref}}{2}$$

where

C_D = drag coefficient

S_{ref} = reference area

In addition to the wake the cross section area of the sting at the downstream end of the test section also has to be accounted for. The corresponding choked area increase in the plenum exhaust valves then is:

$$\Delta A_{PEV} = \frac{A_{sting} + A_{wake}}{(\frac{p}{p_o} \frac{A}{A^*})\, M_\infty}$$

p/p_o and A/A^* are the usual relations found in gasdynamic tables. The effective plenum exhaust valve area required is the area required for a flat Mach number distribution in the empty tunnel plus the increase due to wake and sting blockage shown above.

The plenum exhaust valves are butterfly valves and their effective area increases almost quadratic with the valve opening angle. The drag coefficient of the model also increases in a quadratic manner with the angle of attack. By keeping the plenum exhaust valve at a fixed position up to a certain angle of attack and from that angle linearly ramp the valves with angle of attack the increase in wake blockage can be closely accounted for. In Figure 10 an example can be found showing the plenum exhaust valve modulation with angle of attack and the corresponding amount of air removed.

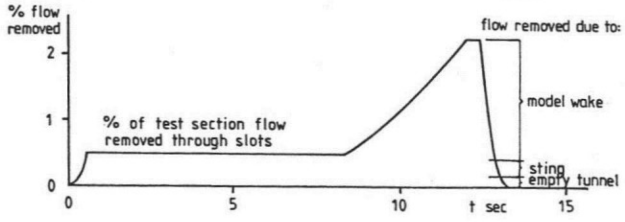


Figure 10. Example of plenum exhaust valve modulation at an α-sweep run and corresponding mass flow removal.

Auxiliary Equipment

In parallel with the design of the wind tunnel itself several other projects were started. For the acceptance test of the tunnel test equipment was designed and built at FFA. They will be mentioned further down where the specific flow property is discussed. Description of other projects follows.

Data Acquisition System

The largest single project beside the tunnel and the building was the development of the data acquisition system. This work was started with the definition of requirements and both hardware and software were taylored to these. The hardware consists of a Digital Equipment VAX 8250, 3 Fujitsu 522 Mb discs, a Phoenix 1 MHz, 16 bit AD converter and 3 16-channel FFA built bridge amplifiers. There are 64 analog input channels. The software consists of about 90 000 newly written statements of executable code, mostly in FORTRAN. DEC's data base handler RDB is used and all user interfaces are through menus. Several users can work with the system simultaneously except for the few critical seconds when a run is taking place. Every wind tunnel project has its own account and password, and unauthorized access to data will thus not be possible.

PSI electronically switched pressure blocks are used throughout when multipressure measurements are done. 5 32-hole pressure blocks are permanently installed in the test section plenum to measure wall pressures. A static pressure pipe to be mounted along the centerline of the tunnel also has 2 pressure blocks. The pressure blocks are calibrated before each run by applying 3 known pressures and a first order least square fit is performed. Due to long plastic hoses the time for the pressure to stabilize is long and consequently a calibration takes about 3 minutes.

For the calibration of pressure transducers a Ruska system is used. With an air supply and a vacuum pump it is possible to automatically calibrate one or more pressure transducers from a pressure table stored in the computer. The Ruska system can be used by both the data acquisition and the control systems.

Balances and Stings

FFA has many years of experience in designing and building strain gage balances. However with the advent of the T1500 larger and more highly loaded balances had

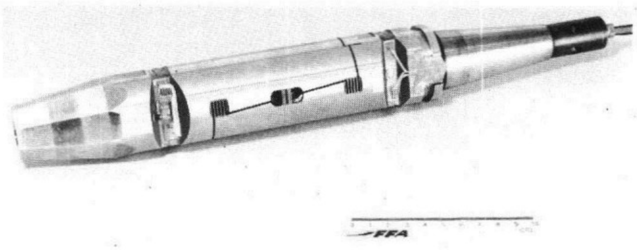


Figure 11. Photo of the 60 mm balance I-684.

to be developed. The balances are of the bending beam type and manufactured of one single piece of steel by the spark erosion technique. Careful attention was also given to the joints between balance and sting and model and sting. The balance-sting joint is a conical taper which is assembled and disassembled with a special tool. The balance-model joint is an octagonal taper which fixes the model both in pitch and roll. The following two 6-component balances have been manufactured.

Balance designation		I-683	I-684
Diameter	mm	48	60
Normal force	kN	19	30
Pitching moment	Nm	900	1800
Axial force	kN	1	2
Side force	kN	9	15
Yawing moment	Nm	500	900
Rolling moment	Nm	500	900

A photo of the 60 mm balance is shown in Figure 11.

For each of the balances above a sting has been designed and manufactured. They are made of Vascomax and are fitted to the roll drive. The center of the balances, when mounted in the stings, is located at the nominal center of rotation. In addition to this a sting adapter for the smaller standard FFA stings has also been manufactured.

Balance Calibration Rig

The existing balance calibration rigs at FFA did not have the load capability for calibration of the larger balances described above. For that reason a completely new rig was designed and built. Due to the high loads dead weights were not used, instead air bag actuators pressurized with shop air were used. They are connected to a calibration sleeve over the balance through tension rods on which load cells are mounted. These load cells are calibrated in a separate rig with dead weights.

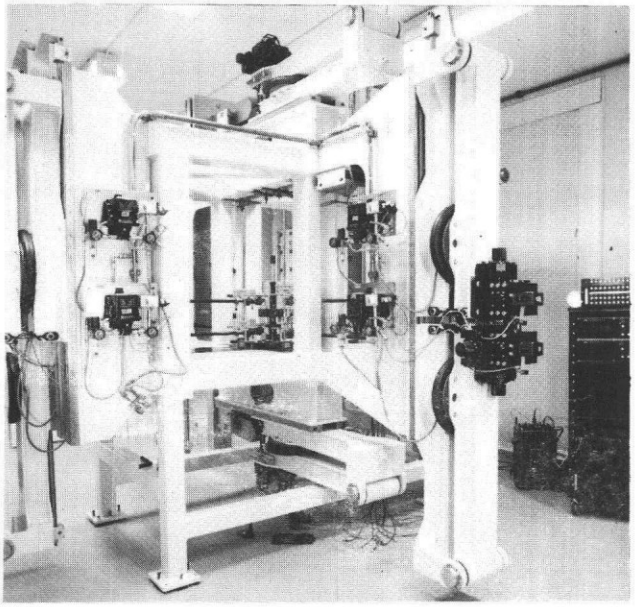


Figure 12. Photo of the balance calibration rig.

The calibration loads are applied to the sting end of the balance. This means that adjustment of the balance due to deflection is not needed. On the other hand the applied loads have to be corrected due to the deflections. The complete calibration rig is computer controlled. From a table in the computer loads are applied, and then balance, load cell and deflection signals are recorded. The computer automatically steps through the different load combinations in the load table. More information on this calibration rig can be found in Reference 3. A photo of the rig is shown in Figure 12.

Schlieren System

A schlieren system has been designed and built for the tunnel. The test section pressure shell has a 600 mm diameter window and in the inner wall rectangular windows are fitted. Their heights are limited to 300 mm due to the presence of the slots. The light path outside the tunnel is seen in Figure 13. Due to the short distance between the building wall and the test section a plane mirror had to be used in addition to the usual two concave mirrors. All schlieren system components are mounted on foundations isolated from the building.

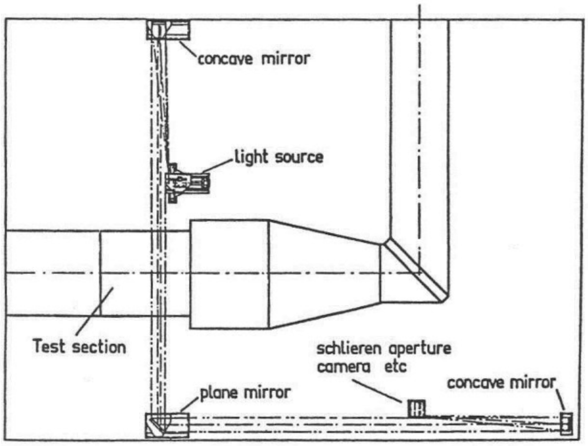


Figure 13. Overview of the schlieren system.

Model Observation System

The test section top wall has been fitted with 6 rectangular windows. Behind these a video camera and several lights can be mounted. The camera is connected to a monitor and a recorder and it will be used on a routine basis for model observation. It will be helpful when performing flow visualization tests in general and in particular when performing sublimation tests.

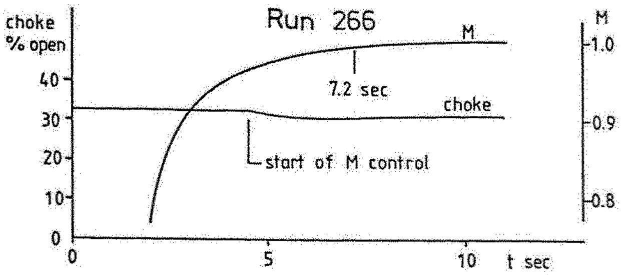
Operating Experience and Test Results

The control of the T1500 in general and to get a rapid start up in particular, was looked at during early design as a major challenge. Considerable work was put into a mathematical model where the running of the tunnel was simulated. The conclusion of this work was that it was possible to run the tunnel as intended and with the required run time at constant stagnation pressure and Mach number conditions. A report on this simulation work is found in Reference 4.

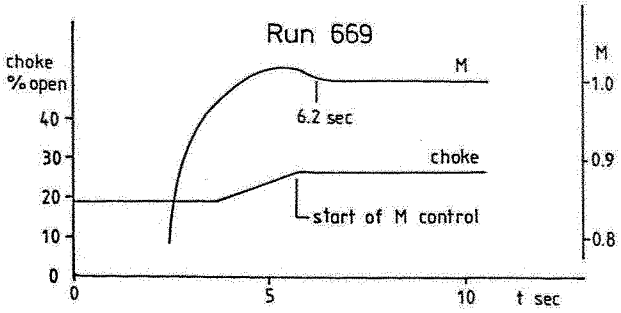
Tuning the Start-up Procedure

Starting the tunnel in the subsonic and also the supersonic speed range is not particularly difficult. Set point Mach number is reached rapidly and is easily controlled throughout the run. Refer for example to Figure 7 where the Mach number is within 0.005 of set point after 3.0 sec. This was a choke controlled run but also a plenum exhaust controlled run as in Figure 8 reaches set point Mach number rapidly, in this case after 4.0 sec.

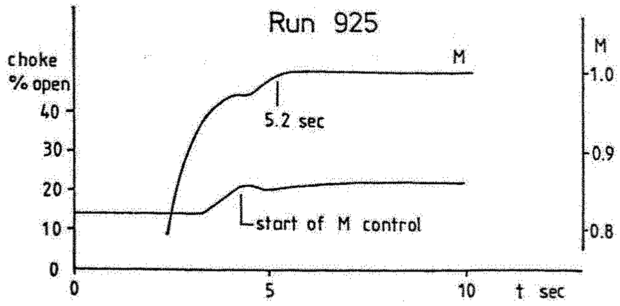
Starting and controlling the tunnel in the Mach number range $0.85 < M < 1.1$ is, however, more difficult. Starting the tunnel as described in choke mode above results in the Mach number slowly reaching set point. For that reason a new procedure was adopted where the choke preset position was more open than the steady state position. After a certain time with the choke at the preset position it was ramped to the steady state position and then the choke control loop was closed. The ramping time was set to 2 sec. Although it takes longer before closed loop control is initiated careful tuning of this starting process makes it possible to be at set point Mach number when closed loop control is initiated. Quite recently further testing has concentrated on reducing the ramp time to 1 sec to get an additional reduction in overall start up time. In Figure 14 examples of the 3 cases mentioned above at $M = 1.0$ are plotted. Here a total reduction of 2.0 sec has been accomplished which is the equivalent of about 3 min of compressor pumping time. This result of tuning the start up process is typical of what has been achieved in the transonic speed regime and it should be possible to improve it still further.



a) no choke ramp



b) 2 sec choke ramp



c) 1 sec choke ramp

Figure 14. Tuning of tunnel start at $M = 1.0$.

Stagnation Pressure Control

The stagnation pressure as measured downstream of the screens in the stilling chamber is the input for the control of the main circuit exhaust valves. There is about a 33 m distance between the stagnation pressure probe and the valves. Nevertheless the control capability is quite good as is shown by Figure 15. Here σ_{p_o}/p_o is plotted against Mach number. The data in Figure 15 is from angle of attack sweep runs with a sting-mounted model. The ratio of model reference area to test section cross area was 0.073, the sweep rate was 5°/sec, and the maximum angle of attack was between 15° and 25° depending on Mach number. The standard deviation is calculated from the control computer printout of 10 readings/sec and the duration is for the actual angle of attack sweep. The data from the $M = 1.4$ was run in plenum exhaust control mode, while all other runs are in choke control mode. The standard deviation is about 0.15% of set point stagnation pressure and is rather insensitive to Mach number.

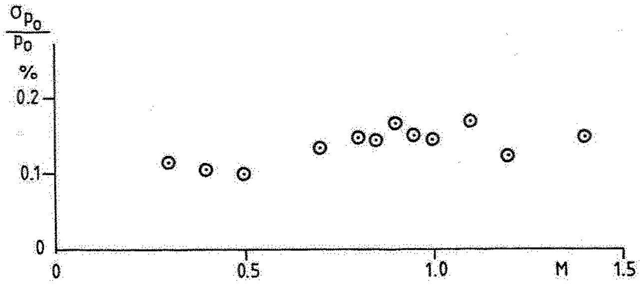


Figure 15. Stagnation pressure fluctuations with a pitching model, $\dot{\alpha} = 5°/\text{sec}$.

Mach Number Control

It is not uncommon for existing intermittent transonic tunnels to lack a fast response Mach number control system. Before a typical run in such a facility the second throat is preset to a certain position and during the run it is not possible to move it fast enough to compensate for a change in losses caused by a pitching model. This means that the change in Mach number during an alpha sweep can be quite significant making it difficult to compare data from run to run, especially at transonic speeds.

The T1500 second throat configuration is designed to be quick acting and to be able to control the Mach number during an alpha sweep. The Mach number standard deviation has been calculated for the same runs as above for stagnation pressure control. The results are shown in Figure 16. Not unexpectedly the largest fluctuations are found in the Mach number range 1.0 - 1.2.

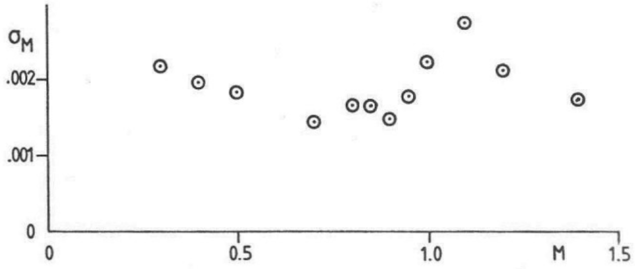


Figure 16. Mach number fluctuations with a pitching model, $\dot{\alpha} = 5°/\text{sec}$.

Stagnation Temperature Variation

As described earlier there is no active control of the stagnation temperature during a run. The data is anyway recorded and it is used for Reynolds number calculation.

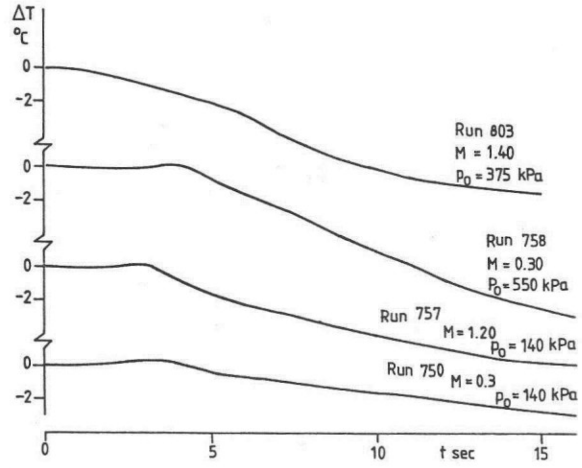


Figure 17. Stagnation temperature shift with time for some runs.

At a typical run the temperature always drops, from 3° to 9°C. The amount of drop depends mainly on run time and thus the ratio of storage pressure at start and stop. In Figure 17 the stagnation temperature change is plotted as function of time for a few randomly picked runs. The four runs picked are located in each corner of the performance envelope. The mass flow rates are thus quite different and in general the higher the rate the larger the temperature drop for the same run duration.

Empty Tunnel Mach Number Distribution

When measurements of the empty tunnel Mach number distribution started only wall data was recorded. These tests were done with the roll drive mounted on the sting pod and fitted with a fairing in front instead of a sting. Initial results showed a dip in Mach number at the model location and an increase in velocity at the downstream end of the test section. This behaviour was found to be caused by the blockage effect of the roll drive. The problem was solved by introducing U-shaped channels as an extension of the slots in the model support section. A plate is mounted in the downstream part of the slot in a way that deblocks the roll drive. This means that the test section now in effect is 300 mm shorter but the resulting Mach number distribution is much flatter, Figure 18.

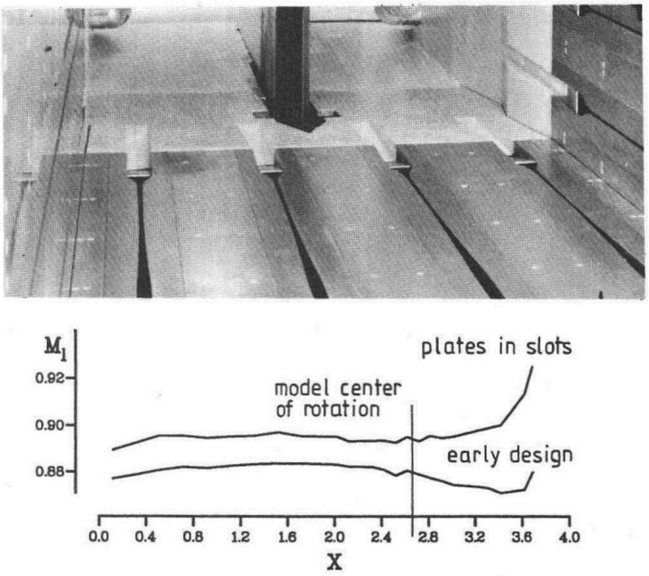


Figure 18. Photo of plates in rear part of slots and their effect on Mach number distribution.

From runs performed at the acceptance test of the wind tunnel and with the centerline static pipe installed the standard deviation and the Mach number gradient has been calculated for several Mach numbers. The axial range used is from 0.75 m upstream to 0.70 m downstream of the nominal center of rotation which is 2.67 m from the upstream end of the test section. The result is shown in Figure 19. M = 1.2 and 1.4 data is near sidewall data as the static pipe was not installed at these tests. The standard deviation of the spatial Mach number distribution is almost constant up to M = 0.95. After that the higher the Mach number, the larger the fluctuations. The Mach number gradient is changing considerably with Mach number. A reason for this is that different top and bottom wall inclinations have been used. At Mach numbers up to 0.95 and at M = 1.2 the walls are 10′ diverged. At M = 1.00 to 1.07 the walls are 20′ diverged, at M = 1.1 they are 12′ diverged and at M = 1.4 they are parallel. As these Mach number distribution tests only are preliminary it is obvious that slightly changed wall settings will be needed for the final calibration to get a flat Mach number distribution.

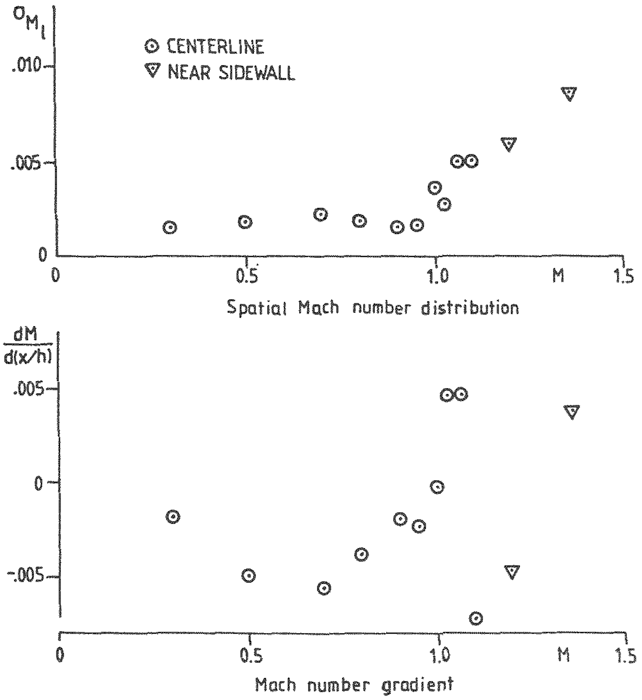


Figure 19. Spatial Mach number distribution and Mach number gradient in the range 1.92 < x < 3.37 m in the empty test section.

Flow Angularity

Only limited flow angularity tests have been performed. These were done with a 4-hole probe mounted in a traverse mechanism and with the probe traversing along an axial line centered at the nominal model center of rotation. Due to uncontrolled deflection in the yaw plane of the mechanism only flow angularity in the pitch plane will be presented. Prior to the test in T1500 the 4-hole probe was calibrated in two other FFA tunnels. As there were no remarkable flow angularity gradients an average was calculated for each run. The results of these tests are shown in Figure 20.

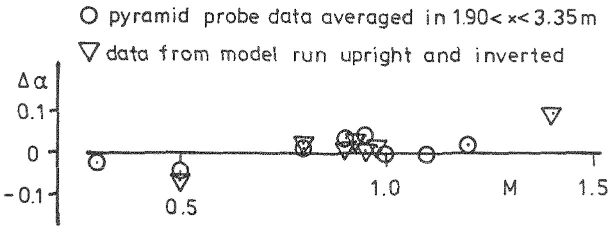


Figure 20. Flow angularity in pitch.

To compare with these results are also results from a sting-mounted model that has been run upright and upside down. The normal force as function of angle of attack curves has been used for the calculation of the flow angularity. The agreement between the two methods is quite good and both show the flow angularity in pitch to be less than 0.1° for all Mach numbers tested.

Test Section Pressure Fluctuations

The test section pressure fluctuation level has been measured in two ways, with two microphones mounted flush with the top wall and with two fast response pressure transducers installed in a 10° cone mounted on the tunnel center line. The microphones were mounted close enough to make it possible to tell from the phase angle between the two signals in what direction the acoustic waves were propagating. Generally it was found that noise was propagating upstream although it was sonic speed in the choke. The cause for this was separation in the model support section upstream of the choke. After modification of the sidewalls in the model support section a significant pressure fluctuation reduction was noted. The present level as measured with the cone-mounted transducers is shown in Figure 21 for M = 0.8 together with results from several other facilities. These results are taken from Reference 5. The broadband value for T1500 is $C_{p\,rms} = 0.83\%$. The FFA results are with solid wall inserts but initial testing has shown a slightly lower pressure fluctuation level with slotted walls. More information on this topic can be found in Reference 6.

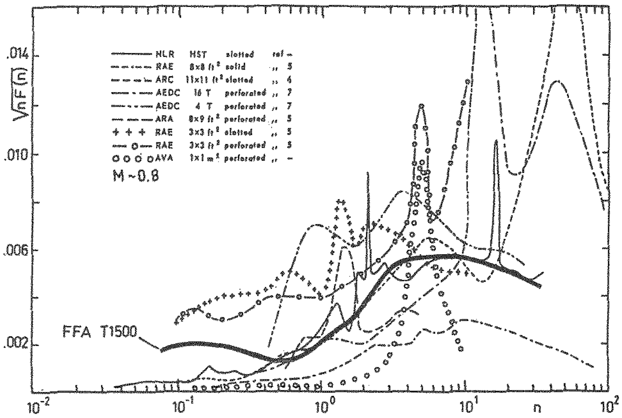


Figure 21. T1500 pressure fluctuation compared with other facilities (Ref. 5).

Turbulence Intensity

A limited turbulence intensity test program has been carried out. For this purpose a three-element hot wire has been used. The intention was to operate the three wires at different overheat ratios, calibrate the probe at different velocity, density and temperature conditions and then be able to reduce the fluctuation level for each component in accordance with Reference 7.

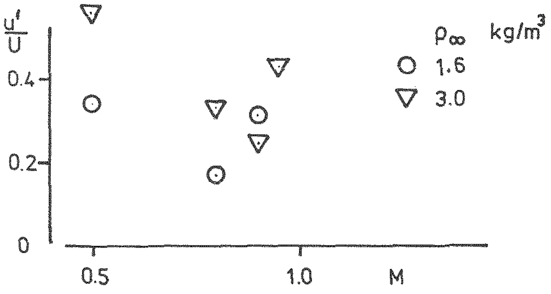


Figure 22. Turbulence intensity.

However, combination of high dynamic loads and dust particles reduced the life of each hot wire to only a couple of runs. For that reason another method had to be used, Reference 8. The new method is a single wire method and by using three wires the tests are triple redundant and wires are allowed to break. To be able to reduce data the assumption that the total temperature fluctuations are small compared to the mass-flow fluctuations is done. Furthermore it was possible to use the actual measurement runs also as calibrations provided that at least two runs at different Mach numbers and the same density could be performed. Tests were done at two different density levels, 1.6 and 3.0 kg/m^3 and the results are shown in Figure 22. This figure shows that in the range tested the turbulence u'/U is about 0.3%.

Current and Future Activities

Current work is concentrated on running different models in the tunnel, models that also have been run in other facilities. Two conformable models of different scales are being run as well as other models with different sizes and aspect ratios. These runs are aimed at verifying the unusual slot shape, the procedure for plenum flow removed with angle of attack and the data reduction methods and programs. 6-component balance measurements together with test section wall pressure measurements are done and the results are also compared with CFD calculations. At the time this is written these tests have not been completed. However, data so far indicate that the test section is a little too closed for low aspect ratio models having a blockage of 0.5% or more. For medium to large aspect ratio models a good agreement with results from other facilities has been observed.

If the slot shape will be modified some models will be retested. After that a more complete calibration of the empty test section will take place.

A half model system to be mounted in the far sidewall is presently being developed. For this system two balances for different load ranges are included. The systems angle of attack range will be from -90° to 90°, it will be hydraulically driven and it will be integrated with the tunnel control system.

Additional internal 6-component balances to fit the load range of T1500 will also be designed and built. Presently a 40 mm balance is in the planning stages.

Conclusions

The T1500 wind tunnel has now performed more than 1000 runs. These have been distributed throughout the whole operating envelope. From these runs it can be concluded:

- Starting time of the tunnel is from 3 to 5 sec depending on Mach number; the closer to M = 1.0 the longer the starting time.
- the stagnation pressure standard deviation is about 0.15% of set point with a pitching model in the test section.
- the Mach number standard deviation is about 0.002 with a pitching model in the test section.
- the stagnation temperature drops from 3° to 9°C during a typical 15 sec run.
- the spatial empty tunnel Mach number standard deviation is about 0.002 up to M = 0.95 and then increasing with Mach number.
- the Mach number gradient dM/d(x/h)</0.005/ and depending on plenum suction, Mach number and wall angle.
- the flow angularity in pitch on the tunnel centerline is less than 0.1° for all Mach numbers tested.
- the broadband test section pressure fluctuation level is $C_{p\,rms}$ = 0.83% at M = 0.8 with solid wall inserts.
- the turbulence intensity u'/U is about 0.3%.

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