A LOW SPEED WIND-TUNNEL WITH EXTREME FLOW QUALITY - DESIGN AND TESTS

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Abstract

Aerodynamic design aspects and testing methodology for the construction of low-turbulence, low-noise wind-tunnels are discussed with a basis in the various design studies carried out in conjunction with the construction of a new wind-tunnel at the Royal Institute of Technology. The design studies were carried out during a five year period and resulted in several publications (see e.g. Refs. 1 and 2) and, above all, a tunnel with a combination of extremely low turbulence and noise levels, along with accurate temperature control etc. For instance the streamwise turbulence intensity is below 0.02 % over the total velocity interval investigated (10 - 60 m/s). The total length of the tunnel is approximately 25 m and the cross section of the 7 m long test section measures 1.2 m x 0.8 m. The maximum velocity is 69 m/s with empty test section.

I. Background

The planning and design stage for the new low-turbulence wind-tunnel (named MTL) at the Royal Institute spanned over approximately a five-year period. The general aim was to construct a wind-tunnel for the purpose of basic research within a wide field of aerodynamics, fluid dynamics in general and even aero-acoustics. Typical long-term research themes pursued by the concerned research group comprise turbulent boundary layers, turbulent processes and their modelling, laminar turbulent transition and several related issues in this area.

The MTL tunnel has several unique features for instance temperature control, five-degree automatic traverse system and is presently equipped with a 7 m long flat plate. Reynolds numbers (Re_x) larger than 20 million can be obtained in the test section. Special care has been taken to ensure very low turbulence intensity (streamwise inten-

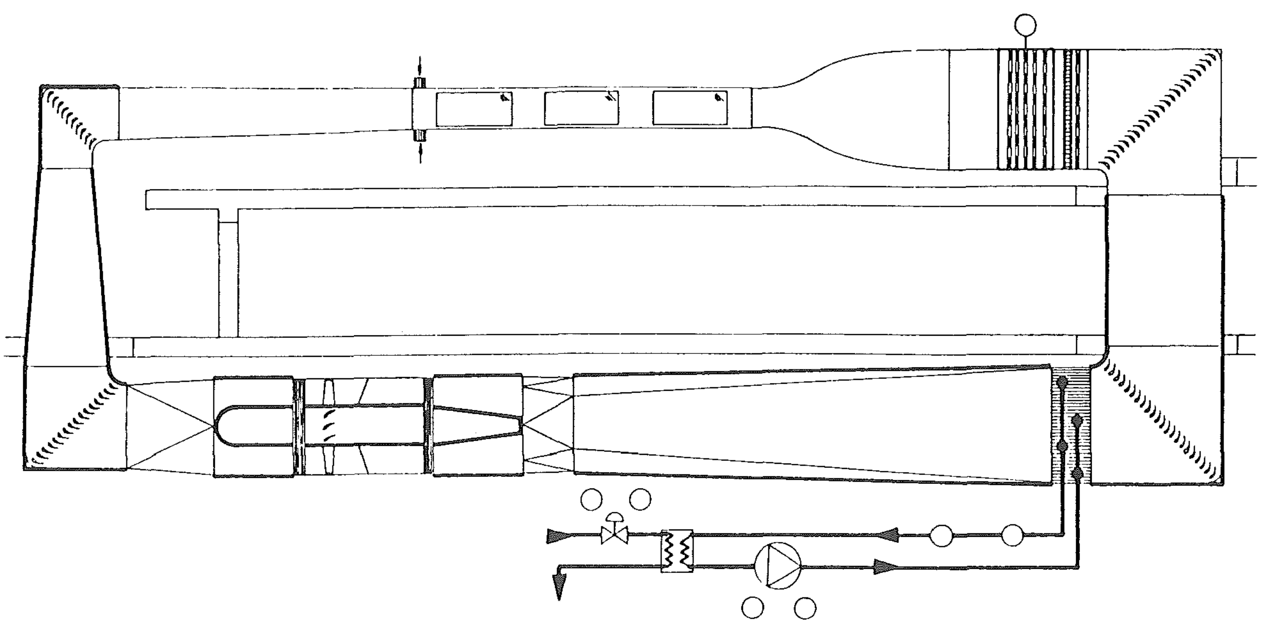


Figure 1 The MTL wind-tunnel circuit. Length of test section is 7 m. Thick lines represent walls with acoustic treatment.

sity less than 0.03 %) combined with a very low acoustic disturbance level in the test section. These features are of particular importance for the studies in the field of laminar-turbulent transition and of laminar separation processes. The low noise level will also allow studies of e.g. wall-pressure fluctuations beneath turbulent boundary layers. Studies of homogeneous turbulence with particular emphasis on turbulence modelling aspects are also planned. A monoplane grid has been built for this purpose that can be positioned in the stagnation chamber. The aspect ratio of the stagnation chamber is the same as for the test section. This enables the study of axisymmetric strained anisotropic turbulence in the contraction and relaxing axisymmetric turbulence in the test section. Both cases have significant bearing on vital issues in the area of turbulence modelling.

The erection of the tunnel was completed in June 1990. A five degree of freedom traversing system, boundary layer plates (7 and 2 m long, respectively) for studies of turbulent and laminar boundary layers, and other peripheral equipment and instrumentation have been completed during 1991. The first serious scientific investigations in the tunnel are presently under way.

II. The tunnel circuit and aerodynamic design studies

Various parts of the circuit were tested in advance in model scale, and particular attention was paid to the minimization of pressure losses and the turbulence damping issue. A study of optimization of screen combinations and turbulence damping by screens in general has been published (Ref. 1). Also detailed model studies and computations were carried out in order to determine the expected damping achievable with the contraction (contraction ratio 9). In general, the aerodynamic design studies were carried out at the Royal Institute of Technology whereas the technical construction aspects were handled by the contractor (SESSIA Inc.).

A side view of the tunnel circuit is shown in figure 1. The various parts and associated design studies will be discussed briefly below. Also, shown in table 1 are estimated pressure losses for the various parts of the tunnel circuit. The tunnel is operated from a movable panel close to the test section. Here, the rpm of the fan and the operational temperature can be chosen.

part	% of Δp-tot
diffusers	31
test section & flat plate	30
settling chamber	19
heat exchanger	11
corners	9

Table 1 Estimated percentages of the total pressure losses for various parts of the MTL tunnel circuit.

Fan, motor and acoustic treatment

The major part of the wind-tunnel circuit has walls with 20 cm thick noise absorbing material (see figure 1). This long-fibred mineral wool is kept in place by a glass fibre cloth covered with a perforated plate. The outer walls are made of a plywood material. Together with cylindrical, noise absorbing central bodies up- and downstream of the fan this gives an excellent noise reduction over a wide frequency band. The damping is less effective at very high and very low frequencies. As is usual for wind-tunnels some very low frequency components are detectable in the frequency range corresponding to standing waves between the corners (around 10 Hz). Other factors influencing the possibility to obtain a low noise level is a conservative design of diffusers (no wide-angle diffuser) and minimization of pressure losses in general in the circuit.

Of primary importance to obtain a low noise level is of course also to have as low rpm as possible of the fan and blade angles adjusted for the load situation. The present fan has 14 blades with the roots at a diameter of 1.2 m and the tips at a diameter of 2.0 m. It rests on a foundation separate from the rest of the building and is vibrationally isolated from the rest of the tunnel elements. It is also equipped with an anti-stall device.

The maximum power delivered to the motor is 86 kW corresponding to the maximum velocity 69.5 m/s in the empty test section.

Guide vanes, diffusers and heat exchanger

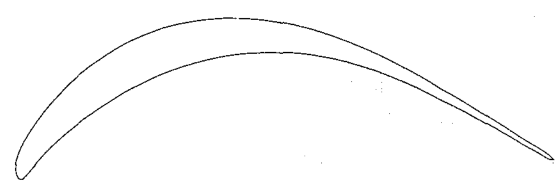
All diffusers are designed to be free of separation and have a maximum equivalent cone opening angle of about 6^o. The first diffuser increases the cross sectional area with 50 % from that f the test section. This together with a new design of the corner guide vanes are important factors in keeping the pressure losses low. The design of the third diffuser (downstream of the fan) was critical in keeping it free of separation, while transforming the cross section from circular to a rectangular one. This was therefore tested in model scale (1:5).

A heat exchanger is situated at the downstream end of the third diffuser. It has elliptical tubing and very thin fins which together acts as a high resistance (see table 1) honeycomb. This has proven to yield both a very good temperature uniformity, and flow quality. The capacity of the heat exchanger is such that a constant temperature can be kept for all velocities. The operational temperature is chosen by a simple control circuit on the general control panel. The operational temperature may be varied, but for reasons of temperature expansion it should be kept within the interval 15 - 30 C. The tunnel elements are allowed to move to accommodate the expansion - contraction due to temperature within this interval.

The heat exchanger within the circuit is supplied with cooling water from an external plate heat exchanger, which in turn is cooled by tap water.

The guide vanes serve two purposes, viz to minimize corner losses and, particularly for the 4:th corner to ensure a good flow quality. The small spacing (about 5 cm) of the vanes gives a honeycomb-like function, which is further enhanced by the fact that the vanes are designed to have attached laminar boundary layers, resulting in a low pressure loss and thin wakes in the flow entering the stagnation chamber.

The corner vanes were designed through use of computations with an inviscid panel method, in which the complete cascade including tunnel walls were taken into account in the computations. The resulting design (see Ref. 2) gave a guide vane with a two-dimensional pressure loss coefficient of about 1/4 of that for conventional vanes consisting of quarter-circles with a straight prolongation of the trailing edge. The required high profile accuracy was obtained by manufacturing the vanes in aluminium by an extrusion process. The vane design presented in Ref. 2 differs somewhat from that finally used, in that the final vane shape and spacing are chosen as to ensure laminar boundary layers. The starting point of the design work was to replicate a pressure distribution on the suction side from one for a well tested low-Reynolds number airfoil (Wortmann FX60-100) on a suitable vane shape that deflects the flow 90^o. The Wortmann profile has been shown to have a low drag at relatively large lift coefficients even for chord Reynolds numbers below 100 000. Advantage was taken of the expansion in the middle part of the cascade to obtain a high pressure coefficient on the pressure side. The vane geometry arrived at in Ref. 2 (shown in figure 2 a) was also tested experimentally and found to give a two-dimensional pressure-loss coefficient below 0.04 at chord Reynolds numbers above 100000 (see figure 2 b).



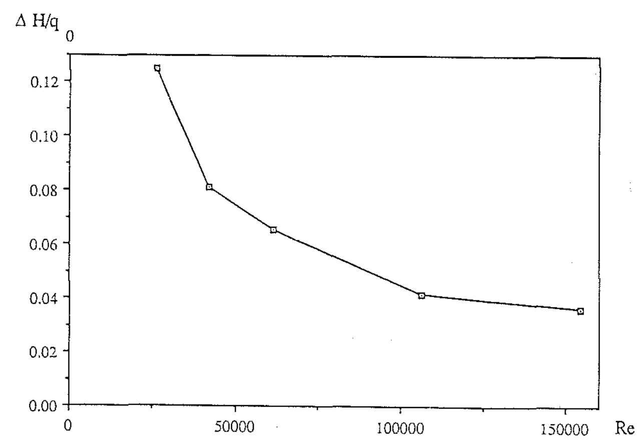


Figure 2 Guide vane (a) geometry and (b) corresponding experimentally determined two-dimensional pressure-loss coefficient (from Ref. 2).

Stagnation chamber

The stagnation chamber is equipped with a honeycomb (cell size 10 mm, length 100 mm, material thickness 0.1 mm) made of thin precision honeycomb material. One removable screen holder is located upstream of the honeycomb and 7 are located on the downstream side. At present a total of 5 screens are mounted on the downstream side (no screen upstream of the honeycomb). The turbulence damping characteristics of the screen package were tested in a separate design study (Ref. 1). The choice of combination of screens arrived at has successively smaller mesh sizes ranging from 3.1 mm to 0.75 mm and solidities below 0.42. The streamwise turbulence intensity is damped by a factor of about 10 through the screen package (less for the cross stream intensities).

A rather unique feature with the present stagnation chamber is a possibility to conveniently pull out the screen holders on rails hidden in the top wall of the stagnation chamber and extending out to the side of the tunnel. This enables easy cleaning of the screens and easy access to the stagnation chamber and a possibility to conveniently mount a turbulence generating grid in the last screen holder. The screen holders ensure a smooth inner wall and an inflatable seal gives an airtight construction.

A straight 1.5 m long section downstream of the screens reduces the intensities and the anisotropy of the turbulence before the flow enters the contraction. This is advantageous since the contraction is less effective in damping the lateral components. The isotropization effect is also made use of in studies of the grid generated homogeneous turbulence.

The contraction ratio is 9 and the total damping of the streamwise turbulence intensity was calculated by use of Reynolds stress turbulence models to be at least a factor of 10. Hence, this fluctuation component is reduced by two orders of magnitude in the stagnation chamber.

The shape of the contraction was determined from criteria of good flow uniformity and minimum risk for boundary layer separation near the inner corners. For this purpose potential flow computations were combined with boundary layer calculations for a large number of variations of the contraction shape. Based on these computations a shape was chosen that was judged to be free of separation even without fillets in the corners. This was also verified to the extent that no separation could be detected from the motion of tufts.

Test section

The 7 m long test section measures 1.2 m x 0.8 m at the entrance. The top and bottom walls adjustable so that a zero or moderate pressure gradient can be chosen. It is open to atmosphere through an air filter at the downstream end. Access to the interior is possible through three large, easy-to-open, front windows, or through three large removable panels on the back side, or through removable panels in the test section floor. A very good rigidity and low level of vibrations is achieved by a heavy steel frame work surrounding the 30 mm thick walls. The traversing equipment makes use of a slit in the upper wall.

The whole test section rests on a carriage that can be rolled out on rails in the floor.

III. Traversing system and boundary layer plates

A five degree of freedom probe traversing system has been built, based on dc servo motors equipped with optical encoders. The vertical direction is that of the translational degrees of freedom with the finest resolution. The encoders and the servo system are capable of positioning with an error less than 1 μm. Yaw and roll angles are adjusted by mechanisms at the tip of the 1.5 m long sting built in carbon fibre. The yaw angle resolution is about 1/30 degree. The tip of the sting, which can be yawed and rolled, can hold various types of probes or probe holders, such as hot-wires or Pitot tubes.

The sting is mounted on a carriage that ca be translated in the spanwise direction along a horizontal wing, which in turn is mounted on a vertical wing that protrudes through the slit in the upper wall of the test section. This enables vertical traversing. A large carriage runs on rails on top of the test section. The vertical wing is connected to this carriage, which hence takes care of the motion in the streamwise direction.

To avoid high frequency electrical disturbances the motors are driven by dc (non-switched) amplifiers. The control cards are mounted inside a Macintosh computer and are handled by use of LabView software. This makes for easy integration with sampling and A/D conversion of signals for which we at present also use LabView software MacAdios hardware.

Two different boundary layer plates are at present used for laminar-turbulent transition studies and high-Re turbulent boundary layer studies, respectively. The first is 2 m long and equipped with a leading edge that was designed to minimize the suction peak close to the leading edge. It is also equipped with a flap. The first experiments with this plate have yielded interesting results and have in several respects demonstrated the high quality of the tunnel.

The second plate is 7 m long, has an elliptical leading edge, boundary layer trip and a flap. It is built in seven 1 m long sections, one of which is designed to be instrumented. The location of the sections can interchanged, still ensuring very small step heights between the sections. Both plates are built with an internal frame work structure of aluminium square tubing, covered with aluminium plates.

The first turbulent boundary layer experiments have also shown that the traversing equipment is extremely accurate in the positioning of probes. Measurements with small hot-wire probes in the thin viscous sublayer have been shown to be quite feasible down to 10 μm or less from the wall. The limitation in this respect is actually set by problems with heat conduction to the wall.

IV. Mean flow and temperature characteristics

The tunnel is operable at velocities from 1 to 69.5 m/s in the (empty) test section. Above 10 m/s the free stream mean velocity remains constant within 0.1 % during continuous operation.This is possible thanks to an accurate temperature control.

The operating temperature of the tunnel is chosen with the interval 15 - 30 C, and can be kept constant for the entire speed range 1-60 m/s. The temperature is constant within $\pm 0.3^{\circ}$C after an initial start-up time of 10 minutes. The coordinate system used in the following presentation of performance test results is as follows. The x-axis is in the streamwise direction starting at the test section inlet. The y-direction is in the vertical direction from the top to the bottom wall. The z-direction is along the span with zero at the right wall looking downstream in the test section. The performance requirements were required to hold within a 'central' part of the cross section. The results presented in the following were taken at x=0.7 m, where the central part was defined as the total cross section excluding a region within 0.10 m from the walls.

The temperature distribution over the test section cross section is constant within less than ±0.2 C.The long-time temperature stability and distribution were measured with a Pt-100 sensor. The measured temperature deviation from the centre of the test section cross section are visualized in figure 3 at the respective location of each measured point.

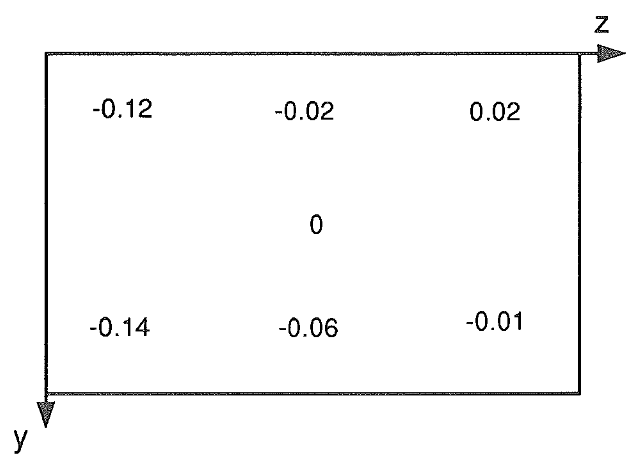


Figure 3 Temperature deviations (in C) from that at y=z=0 for U=50 m/s (x=0.6 m). Temperatures are shown at the respective location in the cross section.

The uniformity of the mean flow was checked by measurements of the difference in total pressure between a fixed position in the stagnation chamber and chosen positions in the test section. The total pressure in the settling chamber was measured with a Pitot (total pressure) tube and the total pressure in the test section was taken from the total pressure hole of a Prandtl tube. The Prandtl tube was traversed in a cross stream plane at 0.7 m from the inlet. The difference in total pressure between the two tubes was measured by a low range pressure transducer (range 0-200 Pa). (A velocity difference of 0.1 % at 60 m/s corresponds to a pressure difference of 4.3 Pa). The variation of the mean velocity can be chosen within a moderate range by adjusting the top and bottom walls.

The pressure difference measurements at 25 m/s are illustrated by a contour plot in figure 4. The contours range from 0.0002 to 0.0020 of the dynamic pressure (at the centreline), i.e. a variation of ± 0.1 % in total pressure, which in turn would correspond to a ± 0.05 % variation in freestream velocity.

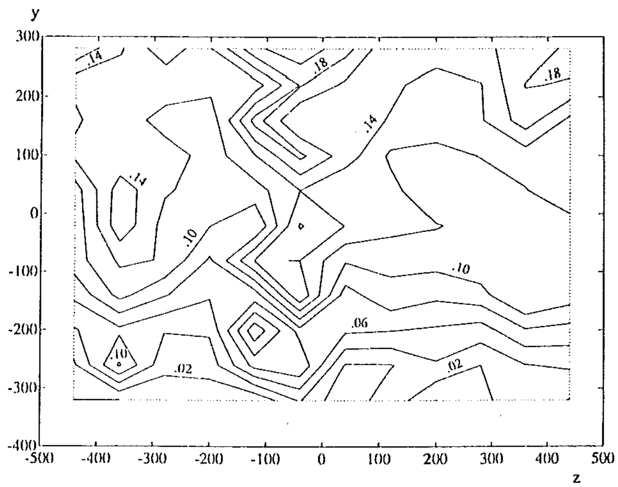


Figure 4 Iso-contours of difference in total pressure in the test section relative to a reference in the stagnation chamber. Contour spacing: 0.0002 of the centreline dynamic pressure. x=0.7 m, U=25 m/s. Numbers denote contour levels in percent. (Coord. system origin here the tunnel centreline)

The variations in flow direction was measured by a specially built probe sensitive to small variations in flow angle. The geometry of the probe is such as to enhance the pressure difference between the two sides of the leading edge of the probe (see figure 5).

The probe was built particularly for the present purpose and the calibration of it yielded a linear relation between the difference in pressure between the two sides and the flow angle within the interval of ±0.7° for which it was calibrated. The probe has a good sensitivity with a

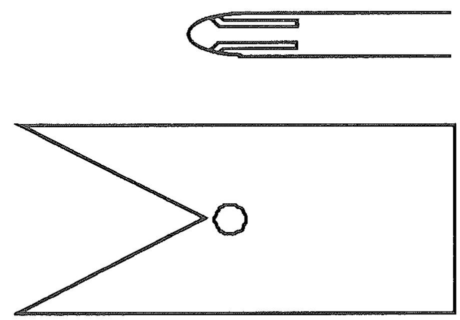


Figure 5 Pressure difference probe for measurement of small flow angles (upper view is a cut through the middle of the probe).

calibration constant of 12.51 degrees/Pa, which gives a good resolution with a low range pressure transducer. Measurements were carried out at 50 m/s and 25 m/s. The bulk of the data were taken at 25 m/s. The data at 50 m/s were similar to those at 25 m/s and are not reported here. The results are illustrated in figure 6 in terms of vectors in the cross stream plane and show that all measured data fall well below ±0.1 °.

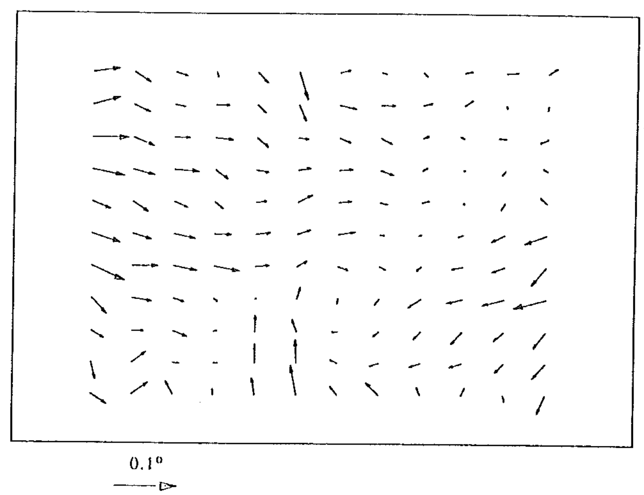


Figure 6 Vectors showing the flow direction in the cross stream plane (x=0.7 m, U=25 m/s). The absolute magnitude is given by the length of the vectors, to be compared with the 0.1 ° reference vector. (Frame signifies the location of the test section walls).

V. Turbulence characteristics

Measurements of streamwise and lateral turbulence intensities were carried out at a number of different speeds near the inlet of the test section (around x=0.7 m). Hot-wire anemometry was used with single and X-probes with 1.0 mm long 5 µm wires. The original performance requirement for the streamwise turbulence fluctuations was that the rms-level in the central parts of the test section should be less than 0.03% of the free stream velocity, for all velocities within the speed range 5-60 m/s. As streamwise turbulence fluctuations we here regard all frequency components that corresponds to lengthscales in the interval 2.5 mm and 2.5 m. The requirement for the lateral components was set to 0.09 %. The higher level is motivated by the expected anisotropy downstream of the contraction.

The sampling and data processing were carried out on a Macintosh II computer using LabView sampling routines and MacAdios A/D hardware.

Results are shown in figures 7 a,b for a freestream velocity of 25 m/s, but similar results were obtained also at e.g. 50 m/s. In general one can say that the streamwise turbulence intensity is practically independent of the velocity whereas the lateral components tend to increase somewhat with increasing speed. At, e.g, 10 m/s the lateral intensities are even smaller than the u_{rms} but at 60 m/s the lateral intensities are just below 0.04 % around the centreline region.

The streamwise intensity is below 0.03 % in the total 'central region' and for a large part of the cross section it is below 0.015 % (figure 7 a), which indeed is remarkably low.

The vertical component of the turbulence intensity is below 0.02 % near the centreline (figure 7 b), but shows somewhat increased levels along a vertical cut that coincides with the location of one of the joints in the honeycomb (made in three parts). Still the levels are below 0.06 % for practically all of the investigated region.

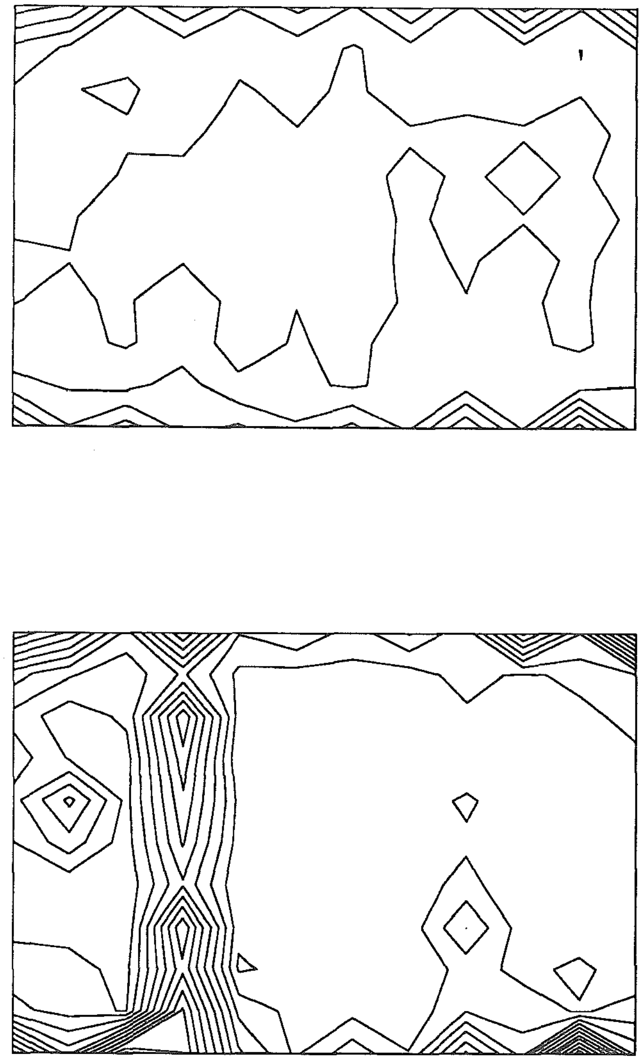


Figure 7 Iso-contours of (a) streamwise turbulence intensity (in percent of freestream velocity, U=25 m/s), Contours start at 0.010 %, increment 0.005 %, (b) vertical turbulence intensity . Contours start at 0.015 %, increment is 0.005 %. Region showed extends from (y,z)=(120,160) mm to (y,z)=(720,1040) mm.

VI. Noise characteristics

The acoustic treatment with noise absorbing material on most of the walls and the central noise absorbing bodies up- and downstream of the fan have given a very low noise level. The requirements on acoustic noise levels are set so that, e.g., investigations of turbulent wall-pressure fluctuations would be possible. The final requirement set was set to a sound pressure level of 0.00015q, where q is the dynamic pressure in the test section, as measured within the frequency interval 60 Hz - 30 kHz. Some very low frequency components (around 10 Hz) can be seen in a measured spectrum and correspond to standing waves between the corners. The prescribed level was required for the total velocity interval up to 60 m/s. In general one may say that it becomes increasingly difficult with increasing velocity to satisfy a criterion set in this way. It also becomes increasingly more difficult to carry out the sound measurements. Various types of measurement techniques were tested. The first method tried was to measure the pressure fluctuations beneath a laminar boundary layer on a flat part of a relatively short wing with an elliptical leading edge. This and other preliminary methods proved to be unsatisfactory for the present purpose.

The final noise measurements were carried out with an 1/8 inch microphone (Brüel & Kjaer plus dito preamplifier etc) pin-hole-mounted inside an axisymmetric body (see figure 8) with a pointed nose. The pressure hole was 0.5 mm in diameter and was placed 83 mm downstream of the nose. At this position the flow is still accelerating and the velocity deviates less than 0.5 % from the free-stream velocity. The microphone assembly was calibrated in white noise against a 1/4 inch Brüel & Kjaer microphone with known gain.

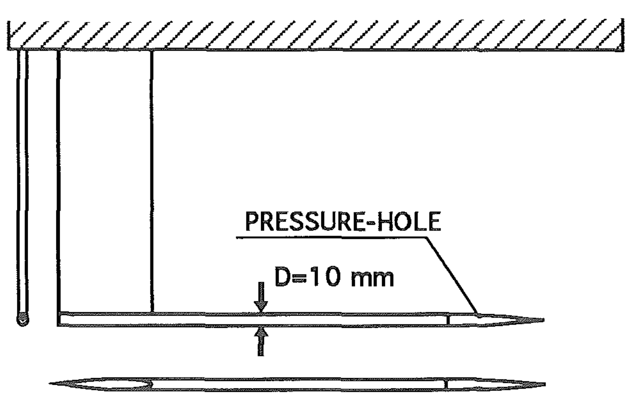


Figure 8 The sting-mounted microphone assembly. The vertical wing protruded 0.3 m from the ceiling.

The transfer function between the two microphones exhibited a Helmholtz resonance at 5 kHz. In the wind tunnel noise measurements the spectrum was divided by this transfer function in order to obtain the true noise spectrum. Thereafter the part of the energy below 60 Hz was subtracted from the total. A Brüel & Kjaer amplifier was used for the noise measurements and the sampling rate was chosen to be 12.5 kHz. Other types of measurements showed that the high frequency (> 5 kHz) contributions to the noise were very small, which justifies the present choice of sampling frequency and microphone arrangement. One should note that the inherent noise level in the microphone used is 64 dB which means that only the requirement at high velocities could be investigated.

The noise levels deduced in this manner at 35 m/s and 60 m/s were 69.1 dB and 82.8 dB, respectively. This is below the required level of 0.0015q, which corresponds to 75 dB and 84 dB, respectively.

VII. Summary and plans for the future

Some of the basic characteristics of the tunnel are summarized in table 2. The MTL wind-tunnel is intended to be a national resource in Sweden to enhance cooperation

total length	25 m
test section length	7 m
" " width	1.2 m
" " height	0.8 m
contraction ratio	9
no of screens	5
mean velocity uniformity	< ± 0.1 %
mean velocity angularity	< ± 0.1^{o}
temperature variations (in time)	< ± 0.3 C
temperature uniformity	< ± 0.2 C
streamwise turb. intensity	
in total 'central region'	< 0.03 %
near tunnel centreline	< 0.015 %
lateral turb. intensity (at 25 m/s)	
in total 'central region'	< 0.06 %
near tunnel centreline	< 0.02 %
noise (sound press.level, f>60 Hz)	
at 35 m/s	69 dB
at 60 m/s	83 dB

Table 3 Basic characteristics of the MTL tunnel.

within existing projects and to stimulate new cooperative projects. It is also planned to encourage participation of guest researchers from other countries. The first extended research visit of this kind is presently taking place.

The main use of the tunnel will be in long-term basic research projects, but it will also be used in undergraduate education to introduce modern experimental techniques in aerodynamics, and to some extent in more applied industrial projects. The research areas will hopefully be diverse, which is made possible by the extreme flow quality of the tunnel in terms of low turbulence and low noise levels.

Acknowledgements

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