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The Berlin axisymmetric boundary layer facility

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Abstract – An account is given of the working life of the recently decommissioned axisymmetric turbulent-boundary-layer windtunnel in the Hermann-Föttinger-Institut of the Technische Universität Berlin, and some principal investigations conducted in it. © 2000 Éditions scientifiques et médicales Elsevier SAS

axisymmetric turbulent-boundary-layer / windtunnel / Hermann-Föttinger-Institut

Foreword

I first encountered Hans Fernholz in 1961 when he came to Cambridge as a British Council Scholar, to work with M.R. Head in the Engineering Laboratories. My contacts with him at that time were essentially social, with substantial common interests in music, food and wine. This friendship has continued both on a social and on a professional basis ever since, with his younger daughter living in my flat for two years, and I having been a tenant of his older daughter in recent years in Berlin – and written a small cook-book for her.

His technical work in Cambridge concerned a detailed study of the variations in skin friction in nominally two-dimensional boundary layers [1] using the then relatively new Preston tube technique. His principal interests have continued to lie in boundary layers, with particular emphasis on the provision and interpretation of experimental data. An example is the formulation of the 'halbempirische Gesetze' for the 'outer region', described in [2] which provides a useful bench-mark for the zero-pressure-gradient case. This concern with the quality of data later resulted in the extensive AGARD collection, for compressible boundary layers and covering about 90 experiments, for which he co-opted me from 1974 onwards [3–6]. (Note: The data in these collections is available in electronic form from the TUBerlin.) Recently a further collection of data has been used to examine the incompressible canonical zero-pressure gradient boundary layer [7].

Coupled with this interest in making available the data of others has been an extensive and varied experimental programme in a variety of rigs in Berlin and in joint projects elsewhere [8]. The 'in house' work has mostly involved complex flows with varied combinations of pressure gradients, separation and free stream turbulence, with a marked tendency to prefer axisymmetric arrangements [9,10], most notably in the series of experiments described below. These are characterised by a very careful control of variables, and the development of much appropriate special instrumentation.

Collectively, the data obtained provide a very wide range of difficult test cases for advanced turbulence modelling.

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Symbols

c_F	wall shear stress coefficient
c_P	wall pressure coefficient
u	component of mean velocity in the x, streamwise direction
v	component of mean velocity in the y direction normal to the surface
w	component of mean velocity in the z direction across the flow
u', v', w'	corresponding turbulent velocity components
χ	proportion of time occupied by reverse flow

1. Introduction

In traditional ‘two-dimensional’ windtunnels there are always end effects on nominally two-dimensional models, either directly due to the sidewall boundary layers or to boundary layer development and secondary flows on end-plates mounted in an attempt to minimise the problem. For many investigations the effects are negligible, but for boundary layer experiments this is always a difficulty. In particular, when separated flows are to be studied, there can be no certainty that the experimental flow, which may well show little transverse variation near the centre-line, is truly representative of the nominal planar case. For this reason a large part of the recent boundary layer research in the Hermann-Föttinger-Institut has been performed on axisymmetric rigs.

Of these the most versatile to date has just come to the end of its service life, providing the unusual opportunity to present a history of a complete experimental programme. The original inspiration was the result of experience gained by Professor Fernholz on an exchange visit to MIT in 1966/1967 (Fernholz, [11]; Fernholz and Gibson, [12]; Goldberg, [13]) where a tunnel constructed on similar principles was in use in the Gas Turbine Laboratory (*figure 1*).

It is initially described here in its 1990 configuration, without special features introduced for later investigations. The facility is being replaced by a new version in which the relationship between the test surface and the porous containing wall is reversed, the test surface being on the inside of a solid walled cylinder with a adjustable porous walled centrebody.

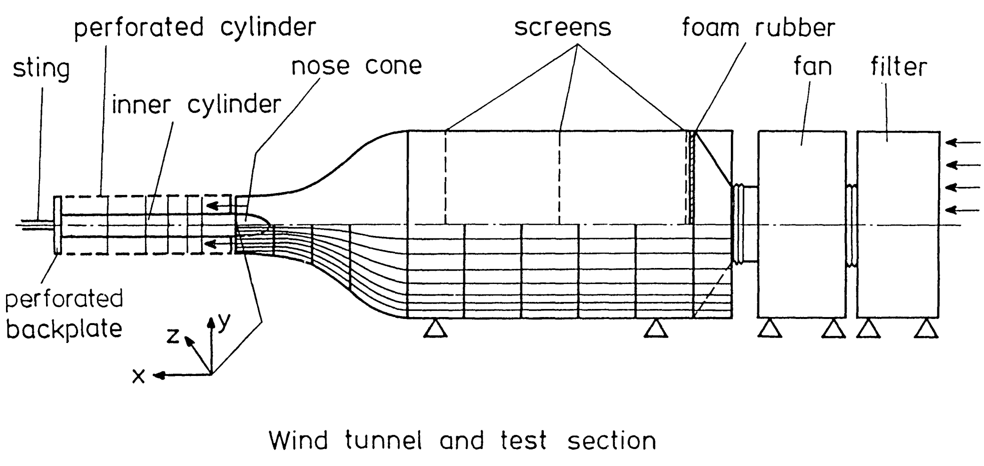

Figure 1. The boundary layer tunnel in its original configuration.

The basic outer structure of the original HFI tunnel remained unchanged from the time at which the settling chamber and contraction were completed in 1971, as an open-jet tunnel (Vagt, [14], following Wille, [15]), until it was finally taken out of commission in 1999. As is usually the case with experimental facilities however, it suffered in some measure from the ‘Irishman’s axe syndrome’. ‘Yes, it’s had a new handle, and, yes, it’s had a new head – but it’s the same axe, mind you’. In consequence, the dimensions mentioned in this note give an attempt at a ‘representative truth’.

2. The facility

The facility was an open return blower tunnel, completely enclosed in an air-conditioned room, which allowed control of the temperature, normally about 21°C, to within ±0.5°, and, if desired, to within ±0.1°, thus avoiding thermal drift problems with hot-wire apparatus. The air entering the tunnel was passed through a filter to eliminate dust particles. The flow was driven by a 12 kW centrifugal fan and entered the cylindrical settling chamber, of length 2.4 m and diameter 2 m, through a wide angle diffuser with two perforated metal screens and a non-woven filter mat. There was a single accurately machined perforated metal screen of 64% open area ratio 0.4 m from the entry, 2 m from the exit. This simple flow conditioning arrangement was found to give excellent results, improving markedly on the original system using woven metal screens (Dengel and Fernholz, [16,17]). An axisymmetric contraction, of area ratio $\sim 11:1$, led to the test section. In ‘standard form’ the flow left the contraction with mean flow velocity uniform to within ±0.5% and turbulence intensity for the streamwise component, u'_{rms}, of 0.2%. A reference velocity was constantly measured by a Pitot-static tube mounted 180° round the test section from the principal area of observation. An in-house micromanometer with a resolution of 0.01 mm of water provided a digital signal at regular intervals (Froebel and Vagt, [18]), used to monitor the very precise fan control system. The unit Reynolds number was kept constant to within about 0.1% with a value in the range $\sim 1.0 \to 1.5 \times 10^6 \text{m}^{-1}$.

The cylindrical test section, with constant diameter $\sim$ 605 mm and length $\sim$ 1450 mm, was unconventional in that was constructed of perforated metal, with 38% open area ratio, and closed or blocked off at the downstream end by a similarly perforated back-plate. Allowing for mounting flanges of $\sim$ 30 mm at each end, the central $\sim$ 1390 mm constitute an area where, by selectively sealing off areas of this surface, and that of the back-plate, outflow through the walls could be controlled so as to manipulate the pressure gradient. The last section of the contraction, 250 mm long, was effectively of the same diameter but unvented and could be regarded as an upstream extension of the test section. Further modifications could be incorporated in the contraction area to adjust the flow field in the test section, and these will be discussed in connection with the individual test programmes described below.

The boundary layer test surface was on a circular cylinder of diameter $\sim$ 250 mm, mounted on a sting and carefully aligned with the axis of the test section. Ignoring upstream modifications, the contraction ratio from the settling chamber to the test surface in the test section was $\sim 13.4:1$. The effective length varied, and the cylinder was fitted with an ellipsoidal nosepiece with semi-major axis 360 mm. A boundary layer trip constructed of Dymo™ tape was mounted at the joint between the nosepiece and the cylinder, which was also usually taken as the zero for x and the effective origin of the boundary layer. The tape, 0.4 mm thick, was printed with ‘V’s at 4 mm intervals, with the apices facing upstream. The overall height of a printed V was 0.65 mm. This trip arrangement, combined with the flow treatment measures in the settling chamber, resulted in a ±1% variation in surface shear stress around the circumference of the cylinder at $x = 1281$ mm in experiment (section 3.3) below. Recently, the tripping arrangements were revised, the final trip being derived from Velcro™ strip with the backing removed.

Instrumentation was either mounted on movable inserts fitted in an axial slot in the test surface, or carried by a traverse gear with a nominal resolution of 0.005 mm. (Corrections for the effect of wind loading were sometimes applied to data obtained close to the test surface.)

Static pressures on the test surface were measured at tappings 0.8 mm in diameter drilled in inserts which fitted into an axial slot, 20 mm wide and 7.7 mm deep, machined in the test surface. The tapping was therefore moved from place to place with its surrounding surface so that any small systematic error associated with the local geometry of the tapping was reproduced at all stations. The remainder of the slot was filled with dummy inserts of varied lengths, allowing instrumentation to be placed and replaced precisely at chosen x-stations. This proved very successful, as in evaluating pressure gradients, smooth curves were obtained directly from two-point differences without resort to curve fitting. Any small systematic error would not be significant for the general pressure level as such.

Wall shear stress was assessed by a variety of techniques. Preston tubes were used generally over the test surface, if the pressure gradients were not too great (Patel, [19]), and served to calibrate other sensors. These, and the Preston tubes, were mounted on inserts similar to that carrying the static tapping and fitted in the axial slot. An interest in the temporal resolution of the wall shear requires that hot-wire based techniques, calling for calibration, must be applied. In regions where there was no instantaneous reverse flow anticipated, 'wall hot wires', consisting of a single hot-wire mounted normal to the flow, parallel to and a small distance above the surface, might be employed (Wagner, [20]). They are not, however, direction sensitive, so that flows with instantaneous back flow (separated or near-separated) were studied using wall-mounted pulsed wire probes (Castro et al., [21]; Dengel et al., [22]). These are time-of-flight devices in which a wire is heated by a short electrical current pulse, releasing heated air which is timed on its passage to cold wires acting as thermometers upstream or downstream. They are therefore capable of giving an indication of the proportion of the time, χ, for which the flow is reversed, and more general statistical information on the temporal distribution of shear stress. A recent discussion of these and other techniques may be found in Fernholz et al., [23].

In the greater part of the flow field, mean and instantaneous velocities were measured with normal hot-wire probes and X-wire probes, using the supporting techniques and equipment developed in-house (Vagt and Fernholz, [24]; Dahm and Vagt, [25]; Froebel and Vagt, [18]). Again, since these are not directionally sensitive, in and near separation regions it was necessary to have recourse to pulsed hot-wire probes. With these it is as yet effectively practical only to make measurements of the streamwise velocity component.

Recently provision was made for measurements with a Laser-Doppler-Velocimeter (Siller, [26]). The seeding particles used recirculated within an inner enclosure, bypassing the filters. This equipment provided two-component data without intrusive disturbance of the sensitive separated flows.

3. Principal investigations

(Note: In the early investigations the origin of x is not certain. Folk memory would place it at the start of the cylindrical test section, but various published dimensions do not agree with this.)

3.1. Measurements in an axisymmetric turbulent boundary layer with weak and strong three-dimensional disturbances (Fernholz and Vagt, [27]*)*

This is the first investigation to be reported with the ventilated working section, and is effectively a preliminary study for that of section 3.2 below. There is a limited description, but the arrangement of the basic tunnel is believed to have been essentially as described in section 3.2. The trip strip was mounted at $x = 6$ mm rather than on the join between the nose-piece and the test surface.

Of general interest is a discussion of the origins, and of the measures taken in the attempt to reduce, the 'weak' disturbances, exemplified by variations in wall shear stress round the periphery of the test surface. As originally constructed, these were up to ±25%. The principal source was tracked down to irregularities in the screens installed in the settling chamber, and after much development effort, the shear stress variations were reduced to ±8% at $x = 79$ mm, with lower values downstream. The 'strong', pressure-induced, disturbances are those introduced deliberately as the subject matter of 3.2 below.

Extensive peripheral Preston tube measurements were made, using Patel's [19] calibration. Flow direction, mean and fluctuating velocities, and Reynolds shear stresses were measured with normal- and X- hot-wires. Measurements covered the upstream region for section 3.2. Some of the downstream data are also reported.

3.2. Turbulence measurements in an adverse pressure gradient three-dimensional turbulent boundary layer along a circular cylinder (Fernholz and Vagt, [28]*)*

In its configuration for this experiment, the settling chamber, of length 2.4 m, contained a sheet of foam rubber at exit from the wide-angle diffuser and three screens, immediately downstream of the rubber mat, and at 1 m and 2.1 m further downstream (*figure 1*). The flow then entered an $\sim 11:1$ contraction. The overall ratio to the cross-section of the flow at the test surface was $\sim 13.4:1$. The mean velocity leaving the contraction was uniform to ±1.5% and the turbulence level as measured (see section 3.5 below) was reported as 0.1%. The back-plate was solid, and set a little back from the end of the test section, leaving an annular gap through which the flow could escape. The plate was tilted so that at the downstream end of the cylinder the flow was forced to become three-dimensional.

The cylindrical centre-body was 1850 mm long (made of Ultramid S$^{\mathrm{TM}}$), the test surface extending over the first 1550 mm, (the origin for x is therefore probably upstream of the start of the perforated test section) with fixed pressure tappings and boundary layer fences ($h \sim 0.1$ mm), for wall shear measurement, mounted alternately along a single generator of the surface. Provision was made for relative rotation of the model and the test section, allowing measurements to be made along any generator of the flow within a limited range. Measurements were made along three generators in the azimuthal range of maximum asymmetry.

The extent to which flow could pass out through the outer cylinder was adjusted to give a steadily increasing pressure as the flow developed. The initial flow was axisymmetric with no significant departure from symmetry occuring upstream of $x = 531$ mm (Fernholz and Vagt, [27]). Profiles were measured at eight stations along each generator, the last station being at $x = 1065$ mm, after which the flow separated. The maximum yaw angle on the surface at the downstream end of the measurement region was of order 30°. Yaw angles fell rapidly as the distance from the surface increased, becoming small in the free stream. Hot-wire data were obtained for mean and fluctuating components of the velocity, and the Reynolds shear stresses $\overline{u'v'}$ and $\overline{u'w'}$. Preston tubes and wall fences (Vagt and Fernholz, [29]) were used to obtain mean values of the shear stress at the wall. A number of investigations of the difficulty and validity of measurements in three-dimensional flow were undertaken. The data are available in an internal report.

It is, perhaps, ironic that the first major investigation in this axisymmetric facility was concerned with a flow in which the symmetry was deliberately destroyed.

3.3. Turbulent and mean flow measurements in an incompressible axisymmetric boundary layer with incipient separation (Dengel, Fernholz and Vagt, [30]*)*

The air supply and test surface were as for section 3.2 (Fernholz and Vagt, [28]), but with the back-plate normal to the axis so as to obtain axisymmetric flow over the full length of the model. The outflow and the width of the annulus were adjusted so as to have a steadily rising pressure leading to an area, effectively at constant pressure, with slightly negative wall shear stress, approximately over the range $850 < x < 1100$ mm.

Measurements, broadly of the same nature as before, were made along a single generator, extending to ~ 1200 mm, with the important addition of pulsed wire measurements for u and u' at the last three stations, where the shear stress was either very low or negative. It was therefore possible to measure mean and fluctuating back-flow velocities, and also the proportion of the time, χ, taken up by reverse flow. The probe was a reduced size version of the original Bradbury and Castro [31] probe, with modifications based on the experience of Dahm and Vagt [24].

This investigation may be regarded as an exploratory version of the next series of tests, section 3.4, Dengel and Fernholz [17], and will not be described in further detail.

3.4. An experimental investigation of an incompressible turbulent boundary layer in the vicinity of separation (Dengel and Fernholz, [17]*; Dengel,* [32]*)*

The outer structure of the facility was unchanged, except that the backplate was perforated and connected continuously to the cylindrical outer surface of the test section. The flow processing arrangements in the settling chamber were changed from those installed for the experiments of sections 3.1 and 3.2 above. A dramatic improvement in flow uniformity resulted, the mean flow velocity becoming constant to $\pm 0.3\%$ ($\pm 1.5\%$) and the uniformity of wall shear stress around the test surface at a representative upstream station lying within $\pm 1\%$ ($\pm 8\%$). This was achieved at the apparent cost of an increase in free stream turbulence, from 0.1% to 0.2%, which, however, is a result of improved measuring techniques, the equipment used in the earlier tests not being able to record the low frequency contribution to the turbulent energy adequately. The best published account of this work is in Dengel and Fernholz [16].

The system of mounting wall measurement sensors on inserts placed in an axial slot was introduced. It appears from a comment in a later paper that the inserts probably had a flat surface exposed to the flow. It is possible, but unlikely, that the discontinuity in transverse surface curvature introduced small secondary flow effects. The axial cylinder forming the test surface had been extended upstream by a wooden cylindrical insert, without instrumentation, providing a greater fetch for the boundary layer to develop before being significantly affected by the pressure gradient. The origin for x is ~ 320 mm upstream of the start of the perforated test section cylinder. It is for this reason that measurements start at $x = 354$ mm. They extend to $x = \sim 1650$ mm.

Three sequences of twelve profiles were obtained in very similar pressure gradients, with an initial rapid rise followed by a more gentle continuing rise over a region of low or negative wall shear stress. The pressure distributions were virtually identical apart from very small differences at the transition from the initial adverse pressure gradient to the gentle continuation. These small differences gave rise to three distinct flow cases (Dengel and Fernholz, [33]). Under, as stated, an identical local rising pressure, the flow remained attached, on the point of separation with zero mean wall shear stress, or mildly separated with negative skin friction in the range $\sim 1100 < x < 1600$ mm. (These statements are to be read in the time-mean sense.) The wall pulsed-wire shear stress sensor allowed an instantaneous assessment of the direction of the flow at the surface. A 50% split between upstream and downstream flow corresponds to the zero mean skin friction point and 'transitory detachment' (Simpson et al., [34]). Note that this could not be detected by a wall hot wire gauge, which would react to flow over it in both directions, without discrimination, for any flow with significant fluctuations.

The data reported consist of wall measurements for up to 21 stations and three sets of profiles for 12 stations. Tables are available (Dengel and Fernholz, [35]) for

c_P, $\mathrm{d}c_P/\mathrm{d}x$, χ_W, c_F, at the wall, with profiles of

$$u, u', v', w', \overline{u'v'}, \chi \text{ (proportion of reversed flow)}$$

and for a range of derived quantities such as integral thicknesses and higher order turbulence quantities. The data sets do not form a complete matrix as certain sensors are only useful for particular types of flow.

3.5. Turbulence measurements around a mild separation bubble and downstream of reattachment (Alving and Fernholz, [36,37]*)*

The outer structure of the tunnel remained unchanged, but the contraction was modified by the insertion of a faired-in ‘throat’ piece at the downstream end, which reduced the diameter to ~ 510 mm (*figure 2*). The contraction ratio between the settling chamber and the throat, with the model installed, was $\sim 18.9:1$. This was followed by a 10° flare 250 mm long, leading to the perforated inner surface of the test section. Just upstream of the throat the boundary layer on the nozzle wall was tripped by a 5 mm copper pipe, so as to avoid separation from the flare downstream.

The cylindrical model providing the test surface was replaced with an aluminium cylinder ~ 1800 mm long, again with diameter ~ 250 mm and an ellipsoidal nose 360 mm long. The trip, at the junction and taken as zero for x, (40 mm behind the throat) was formed from Dymo$^{\text{TM}}$ tape as for previous investigations. The variation of the surface shear stress round the periphery may be seen in Figure 3 of Alving and Fernholz [37]. The back-plate was at $x = 1710$ mm, while measurements extended to $x = 1354$ mm. Wall instrumentation was again installed on inserts which were fitted into a 20 mm slot, but the surface of the inserts was machined to follow the curvature of the cylinder. Instrumentation was as before.

The outer test section surface was left uncovered for the first 80 mm, immediately downstream of the point at which it was rejoined by the throat insert ($x = 210$ mm), the remaining cylindrical surface being impervious, leaving the flow to exit through the back-plate. This arrangement, providing over-contraction followed by diffusion at the start of the test section, was designed to concentrate the adverse pressure gradient towards

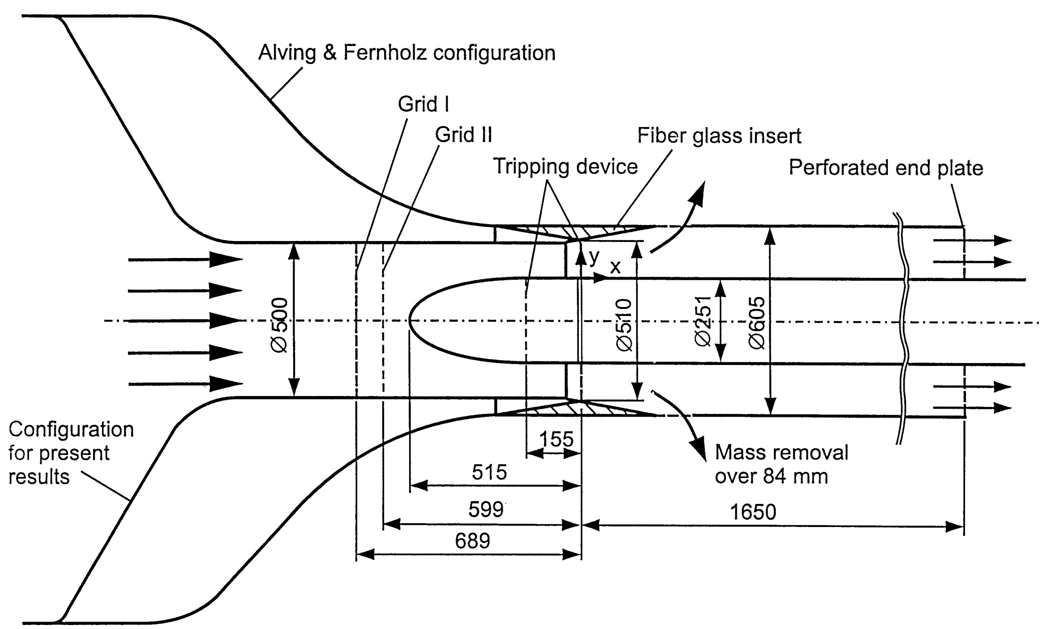

Figure 2. Configuration of the test section for the experiments of Alving and Fernholz [36] and Kalter and Fernholz [39].

the upstream part of the test surface, leaving the pressure nearly constant in an extended recovery region. This is in contrast to the Dengel and Fernholz [17] experiment where the pressure continued to rise over the whole length of the test surface, with the low-shear wall region starting at about $x = 1100$ mm.

The pressure rose rapidly in the range $0 < x < \sim 400$ mm, then remained near-constant, with time-mean reverse flow occurring in the range $361 < x < 518$ mm.

The data reported consist of wall measurements for up to 23 stations and a single set of profiles for 12 stations. Tables are available (Alving and Fernholz, [38]) for

$$c_P,\ \mathrm{d}c_P/\mathrm{d}x,\ \chi_W,\ c_F,\ \text{at the wall, with profiles of}$$
$$u,\ u',\ v',\ w',\ \overline{u'v'},\ \chi\ \text{(proportion of reversed flow)}$$

and for a range of derived quantities such as integral thicknesses and higher order turbulence quantities. The data sets do not form a complete matrix as certain sensors are only useful for particular types of flow.

3.6. The influence of free-stream turbulence on an axisymmetric turbulent boundary layer in, and relaxing from, an adverse pressure gradient (Kalter and Fernholz, [39,40]*; Kalter,* [41,42]*)*

The exterior structure of the facility was unaltered from the last investigation. The interior of the settling chamber and the contraction however were modified by the insertion of a new short contraction, immediately after the machined metal plate at 400 mm from the inlet. This fed into a circular duct of interior diameter 500 mm and length 1050 mm which was in turn faired into the ‘throat’ insert from the Alving and Fernholz [37] experiment (*figure 2*). A principal aim of this modification was to allow for the insertion of turbulence grids upstream with a sufficient fetch for near-homogeneous turbulence to develop.

The test surface was the same aluminium cylinder with an ellipsoidal nose used for the previous investigation. Boundary layer trips at the nose/cylinder junction, taken as the zero for x, and at the throat of the nozzle, were formed of Velcro$^{\mathrm{TM}}$ tape (*figure 3*). Instrumentation was as before.

The pressure distribution was closely similar to that of Alving and Fernholz (section 3.5 above) but the flow remained attached. (Note the sensivity to very slight changes in pressure distribution reported by Dengel and Fernholz above.) Two cases were finally considered, one with no turbulence grid and nominal free stream turbulence (FST) 0.2%, and one with a turbulence grid mounted at $x = -534$ mm, giving a nominal FST of 8%.

Streamwise velocity measurements were made at seven stations, supported by $\overline{u'v'}$ X-wire measurements at five and $\overline{u'w'}$ at two. There are a large number of wall pressure and shear measurements. Time-mean and fluctuating wall shear measurements are associated with the profiles and at up to an additional eleven stations.

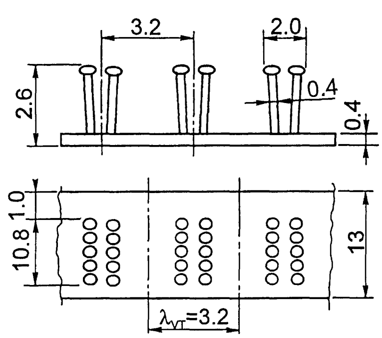

Figure 3. Dimensions of Velcro$^{\mathrm{TM}}$ strip boundary layer trip.

Data tables are in preparation. The published description gives very restricted detail information.

3.7. The reduction and elimination of a closed separation region by free-stream turbulence (Kalter, [41,42], *Kalter and Fernholz,* [43]*)*

In the experiments of Alving and Fernholz (section 3.5) and Kalter and Fernholz (section 3.6) described above, transition occurred immediately before the onset of the adverse pressure gradient. It was decided therefore to reduce the possibility of an interaction between these two features by increasing the fetch for the boundary layer upstream of the start of the pressure gradient. In this experiment the outer structure of the tunnel and the internal modifications to the contraction made for the previous experiment are unaltered, but the test surface has been extended in the upstream direction by 155 mm. The origin for x is unaltered but the trip is still at the junction of the nose and the cylinder, now at $x = -155$ mm.

Extensive preliminary measurements of wall data were obtained by Hauptmann [44] and served to guide the choice of pressure gradients applied. These data are available in tabular form.

There are two data sets. For the first, three cases were considered, one with no turbulence grid, one with 'medium', MFST, nominally 3%, produced by a grid at $x = -599$ mm and one with 'high', HFST, nominally 8%, produced by a grid at $x = -689$ mm. The pressure gradient was adjusted so that a separation bubble extended from $x = 395$ mm to 472 mm ($\Delta x = 77$ mm) with no grid, the 'low' LFST case, nominally 0.2%. The pressure rose rapidly from $x = -100$ mm to about $+670$ mm and then remained substantially constant to the last measurements at ~ 1650 mm. The distributions for MFST and HFST were effectively identical, with the flow attached. The pressure for LFST, separated, flow was slightly lower throughout, particularly in the separated region. No 'plateau' developed, the pressure rose monotonically along the separation bubble.

Streamwise velocity profiles were measured for up to eight stations, supported by X-wire profiles at the first two stations. Mean and fluctuating wall shear was measured at about 30 stations, including pulsed wire results where necessary.

Data available consist of the streamwise velocity profiles for LFST and HFST, with associated reduced data, wall data for all three cases and 'x-profiles' for all types of data at fixed y-values along the length of the surface for LFST and HFST.

For the second set, the significant difference is that the pressure gradient was adjusted to give a slightly more abrupt pressure rise, leading to relatively extended reverse flow. With no turbulence grid in the flow, a separation bubble was formed extending over the range $331 < x < 567$ mm, while with the 'medium' grid, the MFST flow gave a bubble for $300 < x < 406$ mm. With HFST the flow remained attached. The wall pressure distributions for the MFST and HFST cases were nearly identical, while the LFST case, with a relatively large bubble, showed appreciably lower pressure levels in the region of reversed flow. The pressure gradient remained adverse throughout, though it very nearly became zero near $x = 370$ mm in the LFST case. In addition to the probe measurements the flow in regions with significant reverse flow has also been studied with a LDA (Siller, [26]).

A data report is in preparation (1999).

Acknowledgements

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