DOCUMENT CONTROL SHEET

	ORIGINATOR'S REF. NLR TP 96555 U		SECURITY CLASS. unclassified

ORIGINATOR
National Aerospace Laboratory NLR, Amsterdam, The Netherlands

TITLE
General design aspects of low speed wind tunnels

PRESENTED AT
Fall 1996 AGARD-FDP Symposium on "The Aerodynamics of Wind Tunnel Circuits and Their Components", 30 September - 3 October 1996, Moscow, Russia.

AUTHORS F. Jaarsma	DATE 960910	pp 19	ref 14

DESCRIPTORS

Design analysis	Turbulence
Diffusers	User requirements
Flow geometry	Windtunnel balances
Subsonic wind tunnels	
Test chambers	

ABSTRACT
Since the sixties NLR was considering conceptional layouts and airline diagrams for the next generation low speed wind tunnels. This has resulted in the construction of a multi-purpose pilot facility in the early seventies. Based on the experiences gained from this facility, three major wind tunnels have been realized and are in full operation to great satisfaction of the operators and users: namely the DNW (1980) and LST (1983) facilities in the North East Polder in The Netherlands and the ILST (1987) near Jakarta in Indonesia.
In this report the general design considerations in terms of aerodynamic and testing requirements are reviewed and are compared with the actual achievements. Also other operational aspects, such as logistics, acoustics, local constraints, and model supports are considered. From these aspects some lessons learned are concluded and recommendations made.

NLR TECHNICAL PUBLICATION

TP 96555 U

GENERAL DESIGN ASPECTS OF LOW SPEED WIND TUNNELS

by

F. Jaarsma

Paper presented at Fall 1996 AGARD-FDP Symposium on "The Aerodynamics of Wind Tunnel Circuits and Their Components", 30 September - 3 October 1996, Moscow, Russia.

Division	: Fluid Dynamics	Completed	: 960910
Prepared	: FJ/	Order number	: 021.020
Approved	: JWS/	Typ.	: MB/MM

Contents

(19 pages in total)

This page is intentionally left blank.

General Design Aspects of Low Speed Wind Tunnels

F. Jaarsma
National Aerospace Laboratory NLR
Voorsterweg 31, 8316 PR Marknesse, The Netherlands

SUMMARY

Since the sixties NLR was considering conceptional layouts and airline diagrams for the next generation low speed wind tunnels. This has resulted in the construction of a multi-purpose pilot facility in the early seventies. Based on the experiences gained from this facility, three major wind tunnels have been realized and are in full operation to great satisfaction of the operators and users: namely the DNW (1980) and LST (1983) facilities in the North East Polder in The Netherlands and the ILST (1987) near Jakarta in Indonesia.

In this report the general design considerations in terms of aerodynamic and testing requirements are reviewed and are compared with the actual achievements. Also other operational aspects, such as logistics, acoustics, local constraints, and model supports are considered. From these aspects some lessons learned are concluded and recommendations made.

LIST OF SYMBOLS

A	Area
b	width
c	chord
cp	pressure coefficient
k	pressure loss coefficient
L	length
p	static pressure
q	dynamic pressure
r, R	radius
U	axial velocity
u	axial velocity perturbation
x, y, z	axial, horizontal, vertical axis
α	pitch angle
β	yaw angle

subscripts

o	test section, entry diffuser
w	entry Wide angle diffuser

1. INTRODUCTION

In the last decades NLR has been involved in the design and realization of a few major atmospheric subsonic wind tunnels which have found their place in the aerospace development business. These wind tunnels involved in chronological order, the king size German Netherlands Windtunnel DNW, the smaller Low Speed Tunnel LST of NLR, both located in the Northeastpolder near the former fishing village of Vollenhove, and in Indonesia near Jakarta (at Serpong) the interim size Indonesian Low Speed Tunnel ILST.

All three tunnels are based on the earlier aerodynamic design and development work done at NLR as presented at the AGARD Symposium on 'Windtunnel Design and Testing' in October 1975 (ref. 1). This work was based on the earlier plans at NLR to realize a large size low speed tunnel of 8 x 6 m test section (WxH) dimension. This project was then merged with simultaneous plans in Germany for the GUK (Gross Unterschall Kanal) with a specification of two test section sizes, namely 9.5 x 9.5 m and 6 x 6 m, for respectively low and high speeds. The combination of these specifications resulted in the present DNW with three exchangeable test sections and an open test section of 8 x 6 m size for aero-acoustic testing as well.

Tests in the available 1/10th scale model tunnel revealed that the initial circuit design of the 8 x 6 m test section configuration could also accommodate the 9.5 x 9.5 m, 6 x 6 m and open jet configuration meeting all requirements on flow quality as put forward for the GUK and initial NLR plans.
This result could be obtained thanks to a conservative circuit design. More background information on the aerodynamic design aspects of the DNW has been published by Mr. van Ditshuizen in 'Construction book of DNW' (ref. 2).

During the realization of DNW, NLR decided to replace its two small low speed tunnels in Amsterdam by a so-called 3 meter tunnel in the Northeastpolder based on the same circuit design as referred to in ref. 1 for both aeronautical and non-aeronautical testing. Non-aeronautical testing also contains wind-hindrance testing and this type of research requires some type of simulation of the earth natural boundary layer for some surface conditions (e.g. being a flat free field, urban environment etc.). This requires some distance downstream of the contraction to generate and develop the simulated boundary layer before the test article is struck by the wind. Hence a relatively long exchangeable test section arrangement was drafted and realized in the LST.

After completion of the DNW, NLR was approached by the Indonesian authorities for the assistance in the realization of an advanced low speed tunnel at the PUSPIPTEK site near Serpong, West-Java. Size and complexity to be less as the DNW but sufficient for the near and long term needs for the envisaged Indonesian aerospace industry (now IPTN) in development by that time. This tunnel, the ILST, came on stream in 1987 and has since then been in full use for the CN235 and N250 programs. The circuit was slightly modified from the existing well proven design and the 4 x 3 m exchangeable test section arrangement can provide four different combinations for different test purposes and set-ups (ref. 3).

This paper reviews the various components and general aspects of low speed tunnel design and realization, not only from the aerodynamic point of view but also from the users and operations point of view and states, where appropriate, the lessons learned.

2. GENERAL CONSIDERATIONS

For the tunnel user an important parameter is cost vs quality. The cost factor is governed strongly by tunnel productivity and this factor in turn depends, amongst others, on tunnel logistics for interchangeability of model support and test section components. The quality of the wind tunnel data (defined as the degree of simulating free flight) can be expressed in four categories:

- Reynolds number
- Flow quality
- Interference effects (supports, walls)
- Instrumentation and data systems.

This paper deals mainly with the second issue. Interference effects are also linked with logistics and will be considered herein for the wind tunnel configuration concerned (classic, atmospheric). The needed Reynolds no. capability is not considered here. It is usually set beforehand based on aerodynamic considerations, available budgets and other requirements associated with the envisaged usage scenario, such as helicopter testing, noise testing, propulsion simulation, non-aeronautical testing etc. Sometimes, also the available space and/or other provisions dictate the tunnel size and/or type.

When large Reynolds numbers and variations thereof are required for aerospace use as the prime objective a pressurized, close return-tunnel is a good choice as is the DRA 5m tunnel and the ONERA F-1.
Similar characteristics can also be achieved going cryogenic, such as the DLR KKK or use of heavy-gases as was planned in the US recently, but in the latter case Re-variation is problematic. However, the majority of low speed tunnels are atmospheric meaning that either the total pressure or the static pressure in the test section is atmospheric. The test section size then determines the Reynolds number capability.

The maximum speed for low speed wind tunnels for aerospace use is related to the landing, take-off, and climb-out phases of airplanes and therefore should be at least 80 m/s but preferably in excess of 100 m/s. For high-lift systems duplication of the Mach number is of importance to simulate properly the compressibility effects on the wing surfaces. So this prefixes the air speed and hence unit Reynolds number.

The type of atmospheric tunnel for new developments are presently only of the closed-circuit return type what is called in Germany the Göttinger type. Open return tunnels, either via the outdoor environment (such as the added 80 x 120 ft leg to the NASA Ames 80 x 40 ft tunnel) or internally inside a building (DA/Bremen) are hardly considered anymore, because precise and predictably flow conditioning in the test section is not optimal and/or inhouse nuisance. Besides the test section is at sub atmospheric pressure causing sealing and operational problems or at least inconveniencies.

3. FLOW QUALITY SPECIFICATION

The design of the airline diagram (internal shaping) of a wind tunnel and its inserts into the flow results from flow quality optimalization in the test section versus construction and operational costs. In reference 1 flow quality requirements are defined based on acceptable mean flow variations. Compatible with this general requirement is a flow angularity better than 0,1 degree and a turbulence level of less than 0,1 percent.
In a more recent AGARD FDP effort (ref. 4) similar requirements were derived mainly based on the objective to measure drag with a repeatability of one drag count. From this requirement it is necessary to measure overall incidence with an accuracy of 0,01 degrees, local incidence variation along the wing span can be one order of magnitude larger.

In the past the majority of attention to flow quality was directed towards turbulence level with an uniform flow (speed, total head). In the last decades, also requirements are given for flow angularity, static pressure distribution, especially in longitudual direction (buoyancy) and noise level. To this end various older wind tunnels have been equipped with flow rectifying honey combs in the settling chamber and longer and closed test sections to better meet the additional requirements.

4. DISCUSSION OF AIRLINE COMPONENTS

4.1 General airline lay out

The airline used for practically all new low speed wind tunnels is depicted in figure 1. It consists of moderately expanding diffusers, contraction ratio's close to 10 to 1 and a wide angle diffuser in front of the settling chamber. The fan is usually located opposite to the test section arrangement after the flow has passed twice a 90 degrees corner. Somewhere between the test section and

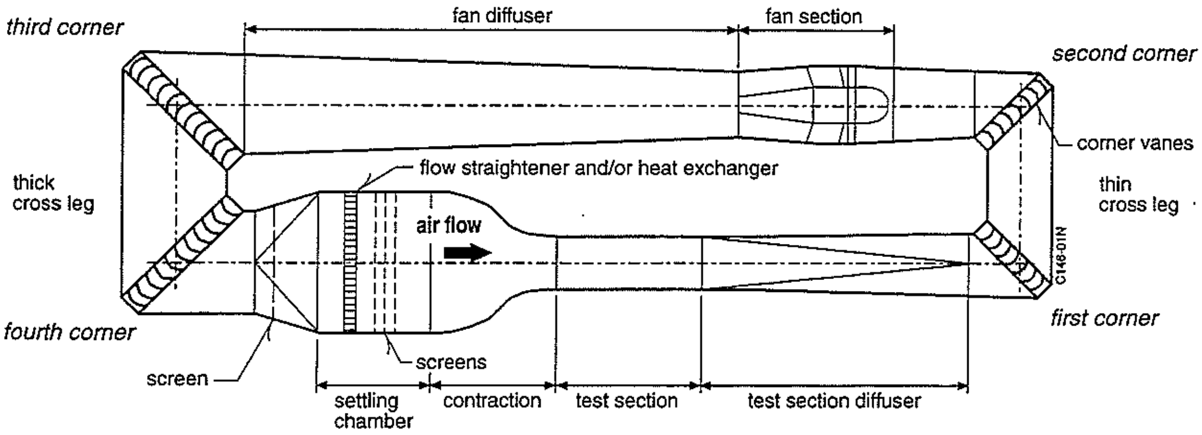


Fig. 1 General Airline Diagram of modern Low Speed Tunnel

the fan a fan blade protector is installed in the form of a screen or honeycomb grid to catch pieces travelling with the flow in case of a mishap with a model in the test section. Wind tunnel fans are practically solely of the axial type and low speed wind tunnels have only one stage with 4 to 10 blades. The combination of the rotating fan with the pre- or aft stator blading provides practically uniform flow to the second (fan) diffuser entry.

Turning the flow around the corner is now-a-days solely done using a cascade of vanes of 90 degrees. In the wide angle diffuser the flow is stabilized by one or two screens to promote uniform spreading. The settling chamber is used to install a heat-exchanger when deemed necessary and here the flow is conditioned as good as possible by installing honeycombs and/or screens.

The circuit is essentially closed but for an atmospheric wind tunnel the interior should be in contact with the environment to equalize pressure at one particular station. A good place for such a breather is at the downstream end of the test section so that it does not disturb the flow around the model but it allows some minor open penetrations in test section walls. This means that the remainer of the circuit is at over pressures and therefore shall be air tight for good efficiency and to prevent flow entry at the breather/test section locations.

4.2 Circuit losses, power requirements

The losses in a wind tunnel circuit, expressed as a decrease in total pressure, have to be compensated by the pressure rise to be generated by the fan. So, in order to establish the necessary power of a wind tunnel, estimates have to be made of the total pressure losses of the various components along the circuit. By adding the individual losses in terms of the dynamic head in the test section the total loss is obtained. Early work by Margoulis, Wattendorf, Parkhurst and Bradshaw should be mentioned in this respect. In a recent study by Wolf an excellent survey is given of the application of this method for compressible flows as generated in transonic wind tunnels (ref. 5). This method is not elaborated further here since it is well established and it has proven its use in practice. In ref. 1, 2, and 5 examples are given of calculating the circuit losses and hence calculating the necessary power to drive the tunnel.

4.3 Diffusers

Diffusers in a wind tunnel are used to recover part of the kinetic energy of the flow in the test section in the form of potential energy finally leading to excess pressure in the settling chamber. To reduce fan drive power, efficient recovery without generating separation is needed. The basis for judgement whether separation may occur is depicted in fig. 2 and is valid for conical diffusers starting from a flat velocity profile at the diffusor entry (ref. 6). With increasing cone angle above a certain value the diffuser will exhibit increasing

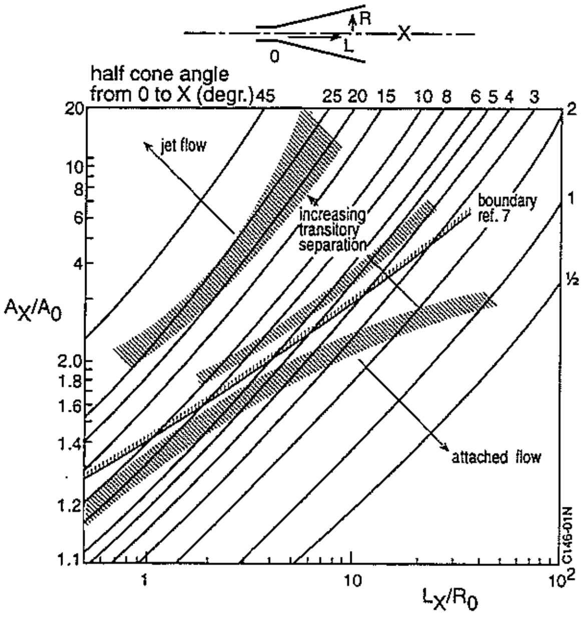


Fig. 2 Flow regime boundaries for conical diffusers

transitory stall causing vibrations and unsteady loading to the fan. At very large cone angles the flow will be continuously separated and the issuing flow can be distinguished as jet flow. Figure 2 also shows the boundary as presented by Wolf (ref. 7). For rectangular diffusers the equivalent cone angles should be 0,5 to 1,0 degrees smaller.

It is essential for the test section diffuser that it is designed very conservatively since the flow downstream of a heavily loaded model may trigger separation earlier then envisaged. In the NLR wind tunnel designs the test section diffusers have an area ratio of about 2 and a cone angle of about 4 degrees. It has been shown that this gave sufficient margin to introduce (insert) a 6 x 6 m test section into the 8 x 6 m test section although with this smaller test section the diffuser is more prone to instabilities.

Rectangular diffusers show strong thickening of the boundary layer in the corners. Therefore it is recommended to use circular, or as a compromise octagonal cross sections where applicable to eliminate unwanted flow phenomena.

Relative to turbulent pipe flow, the total head profile is usually more peaked at the center on leaving the diffuser. Therefore it is wise to make the corner sections cylindrical (parallel) so that some recovery to pipe flow is accomplished. This may allow some additional diffusing action between the first and second corner (in the thin cross leg) but this diffuser shall never be considered as being independent from the test section diffuser. Practice at the ILST has shown that a small diffuser having a 1.1 area ratio can be applied without causing separation problems in this cross leg.

The other item is pressure recovery of the diffuser. Calculations at NLR for the LST 8 x 6/DNW project revealed that optimum pressure recovery (90 - 95%) is obtained for diffuser opening angles close to the upper limit for attached flow as is shown in figure 2 (ref. 2). Besides, it was concluded that the opening angle for optimum pressure recovery decreases with increasing Reynoldsnumber; about one degree (of cone top angle) per one order of magnitude in the Reynoldsnumber.

Since the diffusers cover the majority of the circuit length their crossectional shape is also determined by the construction material. For example, when steel is used it is easy and convenient to make a circular cross section (LST), but when (ply)wood or concrete is used flat surfaces are the more logical choice. At DNW and ILST prefabricated flat concrete slabs were used to construct the circuit having an octagonal cross section. In both cases the experiences were very good because good surface quality and precise and fast surface alignment were possible.

4.4 Corner vanes

The aerodynamic design of corner vanes of the wind tunnels in which NLR has been involved are based on the earlier work of Mr. Zwaaneveld of NLR (ref. 8). Older wind tunnels elsewhere have been modified with these turning vanes showing considerable performance improvements. Turning vanes should be designed for optimal turning effectiveness, rather than for minimal pressure loss.

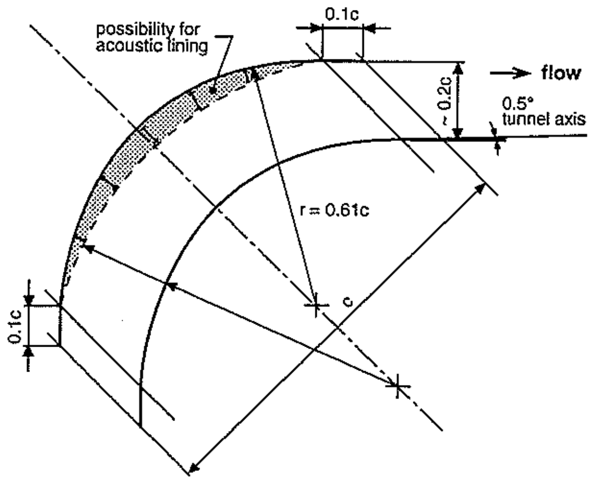


Fig. 3 General lay out of corner vanes

The turning vanes used by NLR consist of metal sheets bend circularly over 90 degrees with both straight leading and trailing edge extensions of 0.1 times cord length. Pitch/cord ratio is 0,2 and the average angle of incidence should be .5 degree. See figure 3. These vanes give room for acoustic treatment at the vane inner corner without sacrificing performances on turning effectiveness and pressure loss (as far as has been observed). To

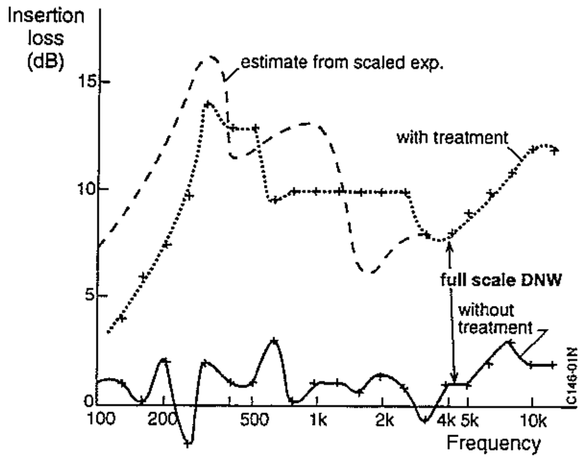


Fig. 4 Insertion loss of lined 1^{st} corner and unlined 2^{nd} corner; no flow

prevent air to flow through the lining material, strips normal to the vane surface should be installed. The noise reduction (insertion loss) due to such a lining is 8 to 13 dB depending on cord/wave length ratio, see figure 4. Such acoustic lining also improves the working comfort within the tunnel because it strongly suppresses reverberation.

One practical remark. From strength point of view the vanes could be made from relatively thin sheets. But from manufacturing, stability point of view a sheet thickness of 8 to 10 mm is recommended with pitch values large enough to pass through. Usually horizontal splitter plates are used to further improve stability to the vane structure.

Diffusing or contracting corner vanes are not or seldom used. Recent work at Boeing showed that both types can be used successfully in their particular application for transforming an existing tunnel into an icing tunnel and to provide additional cross sectional space in between the third and fourth corner (ref. 9).

4.5 Wide angle diffuser

Since efficient and stable diffusion (recompression) of the flow is only achievable in diffusers with limited area ratio's, as has been explained in section 4.3, and since basically only two diffusers are available (the test section and the fan diffuser), a wide-angle diffuser is needed to reduce the airspeed to the level as required in the settling chamber for achieving the desired contraction ratio. In ref. 2 it is argued that by increasing the area ratio of this wide diffuser the turbulence level will also increase at the entry of the settling chamber and this may ultimately increase the turbulence level in the test section with increasing contraction ratio. Figure 5, as taken from ref. 2 and based on empirical computation, clearly illustrates this effect.

A large cross sectional area of the settling chamber will also increase the construction costs considerably because of the large span to cover the (pressurised) chamber and the inserts (heat exchanger, screens, honey combs) to cover the cross section. So, there is a limit to the area ratio of the wide angle diffuser.

The design of this diffuser is based on empirical rules. Without a stabilizing screen the flow will be fully separated (jet flow). However, local separations can not be avoided but are acceptable as long as they are of a steady nature.

The early work of ref. 10 can be used as a guideline to design the screen/diffuser shape combinations. The aim will be to achieve zero pressure efficiency or in other words: the ideal gain in static pressure is used as pressure loss across the screen. It is recommended to confirm the design solution by a scaled model test when possible.

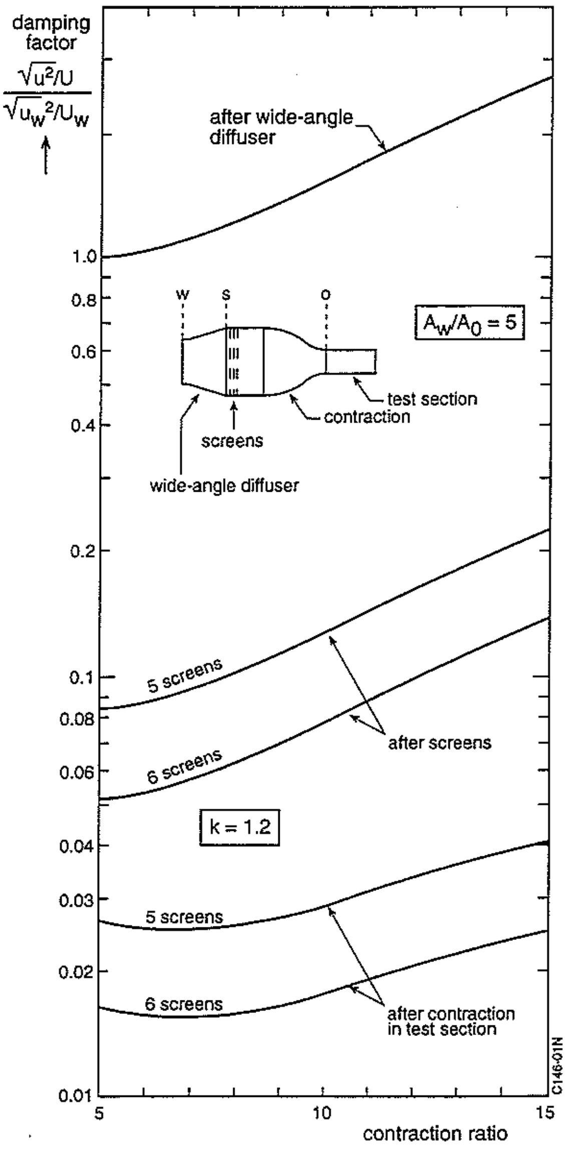


Fig. 5 Damping of Turbulence between 4th Corner and Test Section as a Function of the Contraction Ratio

The drag from the heat exchanger and screen package in the settling chamber will also help to stabilize and spread the flow over its entire cross section. It has been experienced in the model tunnel that when this drag is too large (in that particular case the pressure loss across all inserts was in excess of 6,5 times the local dynamic head) the flow spreading is overcompensated, meaning that the total pressure at the walls in the test section is larger then at the tunnel axis.

4.6 Contraction

For low speed wind tunnels the contraction ratio to be selected will usually be close to 10. With the modern means to condition the flow in the settling chamber in terms of total head, turbulence and flow angularity, a smaller contraction ratio can be selected than was thought of in the early days. As explained in ref. 2, a contraction ratio of 9 to 1 for the 8 x 6 test section of DNW was selected. Therefore, the 9.5 x 9.5 m and 6 x 6 m test section have contraction ratios of 4.8 to 1 resp. 12 to 1.

In principle the design of a nozzle is easy, because essentially the flow goes down hill to lower pressures. The reality is different because:

- there are two potential areas of flow separations, namely at the nozzle entry and downstream of the inflection point;
- cross flow may occur in the boundary layer because of crosswise pressure gradients which may cause large vortices in the test section flow;
- it is desirable to have an uniform velocity and hence static pressure field at the entry of the effective test section;
- it is usually desirable to make the contraction short.

In case of the DNW the design of the contraction was even more difficult because it had to accommodate the three test sections with different cross section sizes and shapes (rectangular and square) starting from a 24 x 18 m settling chamber. Therefore, a special 3-D potential flow code was developed at NLR (ref. 11) to optimise for:

- short nozzles; equal length for all test sections;
- a common interface (as much downstream as possible) for the exchangeable contraction parts to be used;
- prevention of flow separation using the 2-D Stratford criterion.

Use was made of the Börger approach for contraction development (ref. 12). Fig. 6 gives a comparison of the initial 9,5 x 9,5 m contour design (as used with the model tunnel) and the final design in relation to the axial symmetric Börger contour. In recent work at T.U. Darmstadt, Mr. Wolf also used similar methods to cope with his space limitation problem (ref. 7).

An interesting discovery during the development of the DNW nozzle was that the wall pressure distribution in the vertical and horizontal plane of symmetry for the 8 x 6m test section turned out to be almost equal for the width to height ratio along the contraction that was needed to accommodate the 9.5 x 9.5 test section (see figure 7). It is thought that this would have a beneficial effect on the suppression of secondary flows in the boundary layer. Therefore, at the ILST the same contours with varying width to height ratio were selected as well, scaled down from the DNW contour. At ILST the boundary layers at the test section entry were measured during the tunnel calibration program and it was observed that the velocity profiles were non-uniform but very symmetrical along the periphery; see figure 8. The thin boundary layers in the (x-y and x-z) planes of symmetry indicate that there is a secondary flow in the boundary layers from the centers towards the corners. One would estimate that the boundary layer thickness is of the order of the values as measured except for the planes of symmetry.
Contrary to the ILST, the LST has a nozzle with a constant width/height ratio. At the LST nozzle exit this phenomenon is not observed.

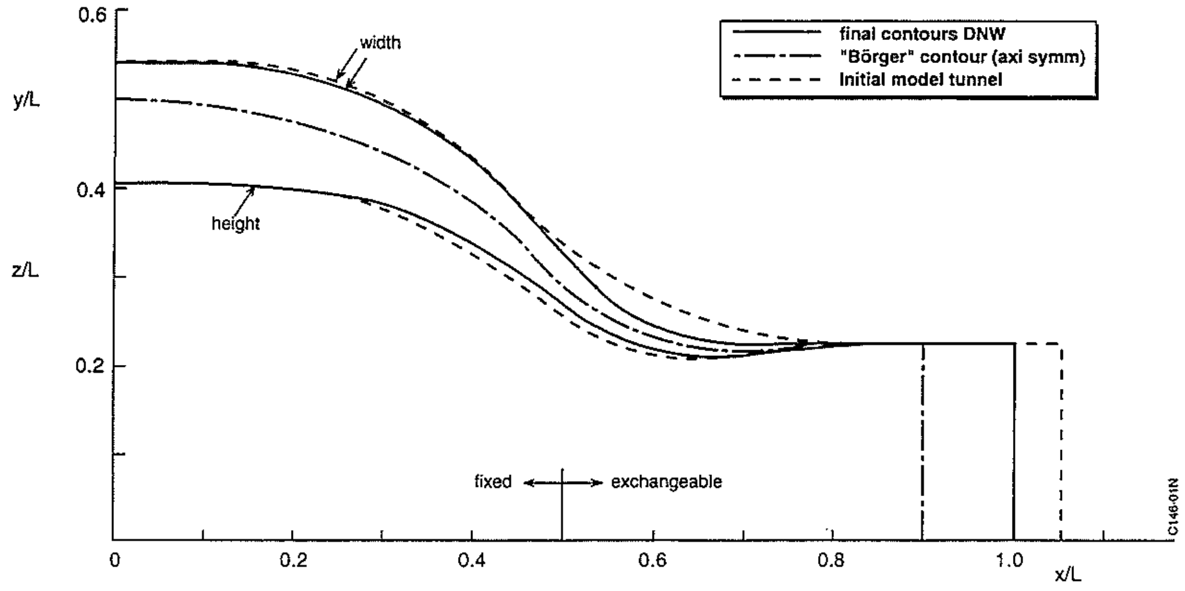


Fig. 6 Contours for the 9.5 x 9.5 m contraction of DNW

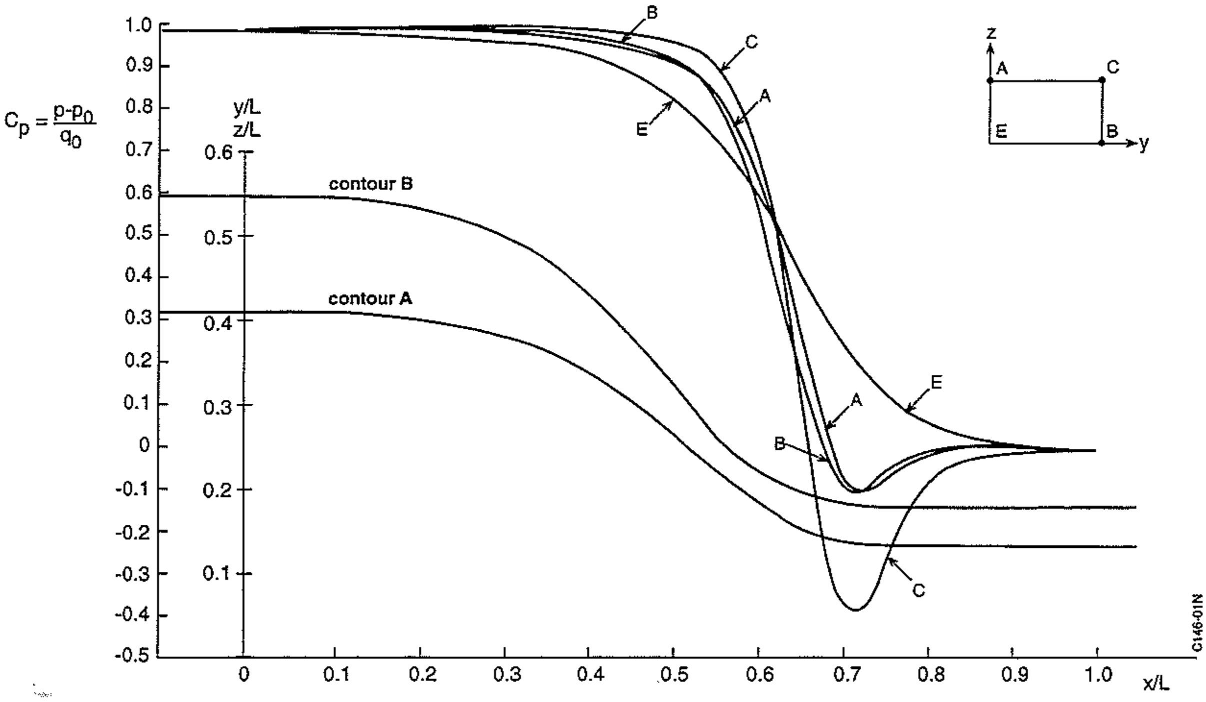


Fig. 7 Wall contours and pressure distribution, contraction 8 x 6 m^2 of DNW

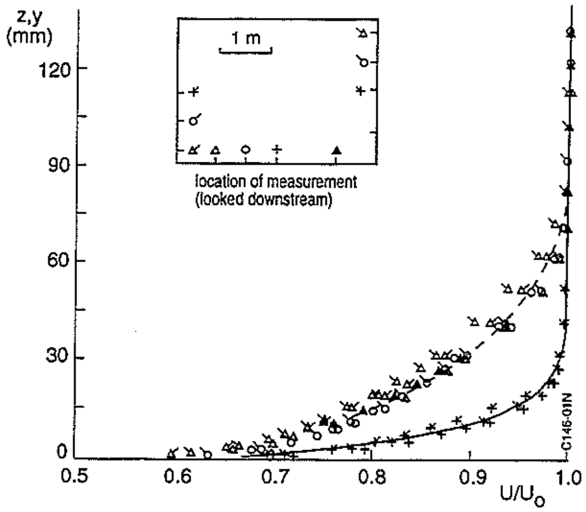


Fig. 8 Velocity profiles in boundary layer at end of ILST contraction

For both methods of Börger and NLR, the nozzles show at the exit a parallel part with a length of about the nozzle height/width in order to arrive at a sufficiently constant static pressure distribution ($\Delta cp \leq$, 0.003) at the test section entry. This parallel part gave the opportunity to install faired inserts in the 8 x 6 m DNW nozzle along the side walls to attain the 6 x 6 m exit for the smallest test section. In this configuration the static pressure field is within specification 3 m downstream of the contraction exit, but this is acceptable because the smaller test section will accommodate also smaller models.

It is recommended to execute some contraction flow computations with modern N.S. codes in order to better understand the viscous flow along the walls and in the corners and to observe in how far secondary flows and/or even separations are a problem, and if so, how improvements can be made. This is even more opportune for designing transonic nozzles. There the shaping is inherently complex since part of the nozzle is two-dimensional in the sonic adjustable throat area. Maybe more data and experiences will be presented later in this symposium.

4.7 Settling chamber

In the settling chamber the flow is preconditioned to obtain the desired flow quality in the test section. Here the following inserts are usually placed into the flow

- heat exchanger, (when deemed necessary)
- flow rectifier,
- anti-turbulence screens and
- (as recently needed) smoke/seeding generator(s) for laser flow visualisation.

It is recommended to place first the heat exchanger in the flow (in downstream order). This device consists usually of finned tubes. For low speed tunnels a single row with about 10 cm long fins is usually sufficient. In the LST no heat exchanger is applied because the power level (or max. speed) is low (80 m/s). Since the steel

circular shell is mainly outdoors no running limitations are experienced except at hot, sunny days.
In order to limit the total pressure loss inside the settling chamber (below about 6,5 times local dynamic head), the tubes used in the DNW and ILST have an elliptical cross section.

The heat exchangers fins basically will have a (lateral) turbulence and flow angularity damping effect but the heat exchangers tubes will cause vortex shedding and when the fins are not placed fully parallel (and horizontal) new stable vortices will be generating behind the heat exchanger. Since the commercial production method of finned heat exchanger pipes is not intended for making perfectly straight fins and fins exactly normal the pipe axis, one should not strive to combine the flow rectifying and cooling function into one device.

Studies at NLR in the model tunnel have revealed that it is very effective to suppress vortex shedding of the heat exchanger pipes by placing the leading edge of the flow rectifier close to the heat exchanger. At DNW and ILST the same configuration was selected with only a gap of 5 mm between the fins and honey comb of the flow rectifier.

The design of the flow rectifier was mainly based on the early work by Humley (ref. 13). It was recommended to select a cell length to diameter ratio between 5 and 10. When the cells are short the flow rectifying function and lateral turbulence suppression function decrease, whereas for long cells the merging of the internal cell boundary layers causes new turbulence.
In all three tunnels, similar flow rectifying panels of about 1 x 2 m size (H x W) were used containing 115 mm deep honeycomb mesh of ½" cells. The cells are made of 0,2 mm aluminium sheet produced by an industrial expansion process. It is experienced in the model tunnel that both the leading and trailing edges of these honeycombs should be completely free of damages, blurs etc., because these minor deficiencies have a measurable effect on the flow in the test section and will not be damped by the downstream screens. It is, of course, also extremely important to inspect, install and align the honeycomb panels very carefully. The honeycomb panels were attached to the heat exchanger structure (DNW and ILST) and it was observed that the wakes from the extruding bolt heads and nuts (downstream from the flow rectifier) could not be traced back in the flow in the settling chamber.

Whereas a flow rectifier has a strong damping effect on lateral flows, screens have this effect on imperfections in the axial flow direction. Three to four anti-turbulence screens are applied in between the flow rectifier and contraction with an open area ratio of 0,57. Ref. 2 gives more details. Since much has been published in the past on screen turbulence damping (see also ref. 1) nothing will be said here about the specific screen characteristics (mesh, wire diameter, open area ratio, etc.).
Instead some practical remarks will be made.

- Since the screen weaving machines do not allow full width screen weaving in one cloth, seams have to be made. Modern plasma welding (wire by wire) or brazing techniques are sufficient (see fig. 9 of plasma welding example).

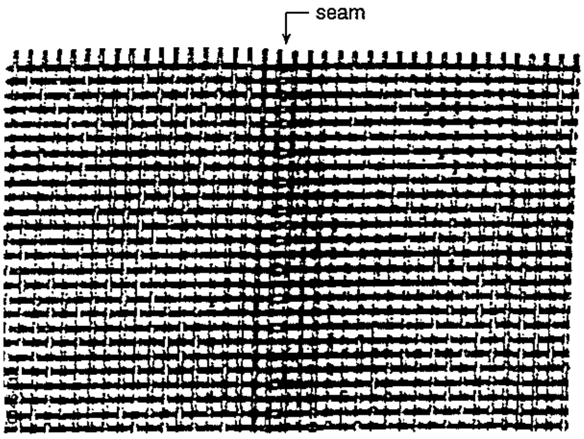


Fig. 9 Screen cloth with welded seam

- It has been shown that deviations in ideal flow direction (flow angularity) in the test section in both ILST and LST in pitch ($\Delta\alpha$) direction is larger than in yaw direction ($\Delta\beta$), see fig. 10. This may be attributed to the weaving direction of the screens. Therefore it is suggested to position the screens such that the waving direction is horizontal. In the ongoing upgrading program of the NLR-HST, the new screens will be placed horizontal. The effect hereof will be published when the results are available, probably in 1997.
- During the commissioning process of the ILST the screens were (apart from being fixed and stretched somewhat to the ceiling and floor) fixed and stretched as well to the side walls. This had the effect that the maximum flow angularity in pitch decreased somewhat from 0,15 to 0,10 degrees (see fig. 10). This finding supports the previous statement on weaving direction. So, screens should be fixed and (slightly) stretched all around its periphery.
- Screens shall be completely free of kinks, sharp bends or other inhomogenities because such imperfections can be traced back in the flow and in particularly for flow angularity.
- The weaving direction of one screen shall be the same; e.g. on both sides of a seam the weaving shall be from left to right or visa versa.
- The distances between the screens shall be large enough to prevent vortex (turbulence) interaction and to allow human entry in between the screens for screen cleaning.

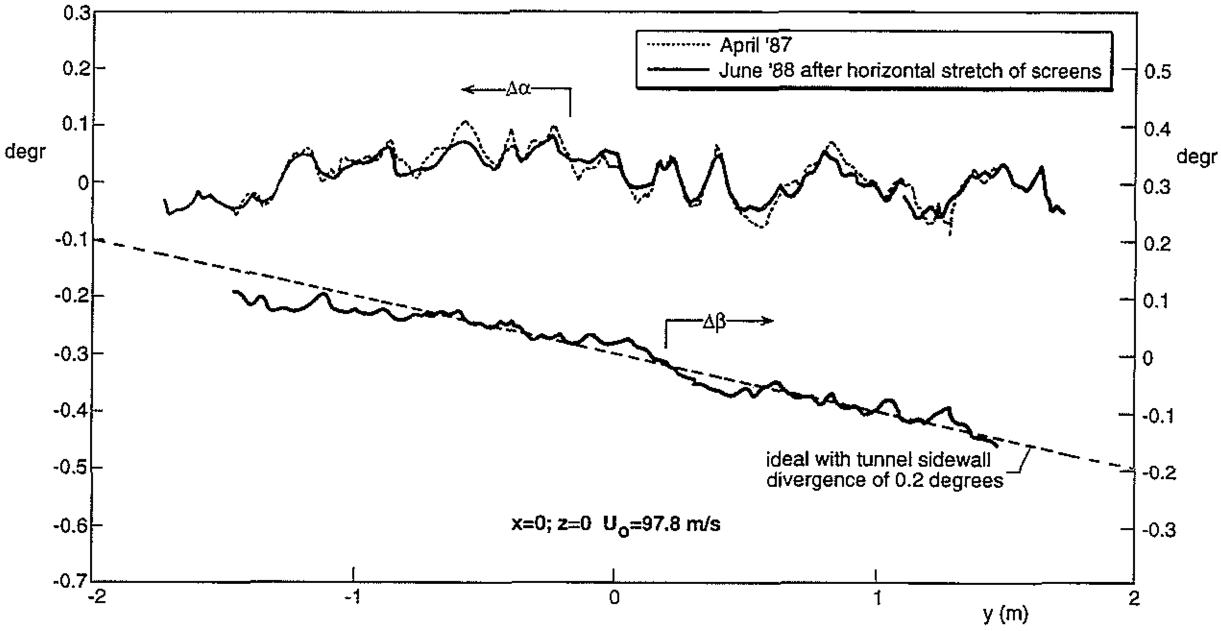


Fig. 10 Flow angularity in pitch (Δα) and yaw (Δβ) along y-axis and the effect of screen stretching in ILST

The turbulence levels in the DNW and LST test sections are very low (0,03 to 0,06 percent), as was established with special measuring techniques during the calibration programs. Since these values are so low, this special effort was not done in the ILST. In a comparative test campaign in the DNW and in free flight it has been shown that the turbulence level in the DNW is below a threshold value for affecting transition of a laminar boundary layer (ref. 14). This shows that the design efforts for the inserts in the settling chamber have been successful and no further optimizations are needed in this respect. This will also be valid for the two other tunnels, LST and ILST.

Recently a fourth item is occasionally introduced into the settling chamber: a smoke or seeding generator for laser flow visualisation studies. In order to pinpoint a certain streamline or streamtube, a traversing device and/or spatially distributed smoke/seeding injector can be used. Exploratory tests in a model tunnel at NLR have revealed that, for stability reasons, injection upstream of the heat exchanger is the most suitable place. Besides, the flow disturbances from these devices are best damped by the downstream heat exchanger, flow rectifier, and screen package. Similar experience is also attained at DNW. Therefore in the NLR's high speed tunnel, HST, a traversing smoke/seeding mechanism will be installed in front of the heat exchanger and whether this device will have to be removed when flow seeding is not needed, has still to be determined in practice by observing flow quality during a calibration campaign.

5. TEST SECTION

The flow within the test section and the test capabilities count for the aerodynamic researchers. Therefore, although the test section is part of the airline, it will be discussed here separately. The following topics will be discussed in this section:

- Test section shape
- Provisions in the walls
- Model supports and logistics.

These topics are interrelated but nevertheless it will be tried to describe them separately.

5.1 Test section shape

Modern wind tunnels have either a square- or a rectangular cross section. It is thought that for high lift testing such as for helicopters or for V/STOL planes, square shapes would be better then the rectangular ones. Experience in DNW has shown for the past 15 years of operation that the rectangular 8 x 6 m test section is used by far the most for aerospace testing relative to the available square 6 x 6 m and 9.5 x 9.5 m test sections, also for helicopter work and high lift devices.
Corner fillets are rarely used anymore. It will disturb the routinely applied wall correction methods and with properly designed contractions, flow separation in the corners can be prevented. Besides, without those fillets the full side walls height and floor/ceiling width are available for easy access and instrumentation.

The test section length should be at least about three times the average of width and height (or $\sqrt{A}$.) (to prevent buoyancy effects from the test section diffuser) with the model center at approximately one third from the test section entry under the conditions that the contraction is designed according to the Börger/NLR approach.

One set of walls should be parallel to accommodate a set of axially aligned turntables in these walls (in the three tunnels considered herein the floor and ceiling). The other set should be diverging somewhat to compensate for displacement due to boundary layer growth along all four walls.
In all three tunnels a value of 0,2 degrees divergence (relative to the test section axis) was selected but it was found that in all three tunnels this resulted in some overcompensation as is shown in table 1.

Table 1 Static pressure gradients at T.S. axis for DNW, LST and ILST

	DNW			LST	ILST	*without* BL
	8 × 6 closed	slotted	6 × 6 closed			
$\frac{dcp}{dx/b_0}$	0.004	0.0032	0.0046	0.003	0.0012	0.014

It may be concluded that a value of divergence of 0,18 or 0,17 degrees would have been a better average choice. Nevertheless, the effect of this buoyancy on drag measurements is only of the order of one drag count or less and therefore can be disregarded for most tests.

5.2 Provisions in the walls

Low speed aerodynamists want to watch their model during tests. Also modern flow visualization techniques require good access to the flow field by passing laser light bundles inside the flow. Therefore all four walls should be equipped with removable windows where possible. Depending on the optical demands various glas qualities may be used. At DNW the windows consists of three sheets glued together to prevent scattering at accidence whereas in LST and ILST plexiglas panels are used. Special glass is to be used when high power laser light bundles have to pass the windows. Window panels are usually removed when necessary to stick probes or traversing mechanisms into the floor. The side walls are further provided with entry doors for human access and at DNW also to enter a cherry picker to reach the model for adjustments or checks.

At ILST and LST a removable test section part is provided with a set of synchronous and axially aligned turntables in the floor and ceiling. Both tunnels also have a similar turn table at the downstream end of the test section for wind hinderance testing.

At LST and DNW sets of almost full test section length rulers with static pressure ports can be installated along the test section walls to measure the wall pressure distribution. They are used for wall interference assessment using methods based on measured boundary conditions. Having available such devices turns out to be very handsome and practical.

Wind tunnel walls are also often used to install a fast acting q-stopper in the form of fast opening doors or protruding panels. The walls of the tunnels under consideration herein are not designed to accommodate such devices. Instead, at DNW an extremely fast q-stopper was developed and designed consisting of a 1 m^3 pressure vessel on the tunnel axis at the entry of the test section diffuser. At trigger a small fast acting valve is opened initiating a set of retro airjets opposing the flow. This causes a weak upstream travelling shockwave that passes over the model. See fig. 11. Model tunnel tests in

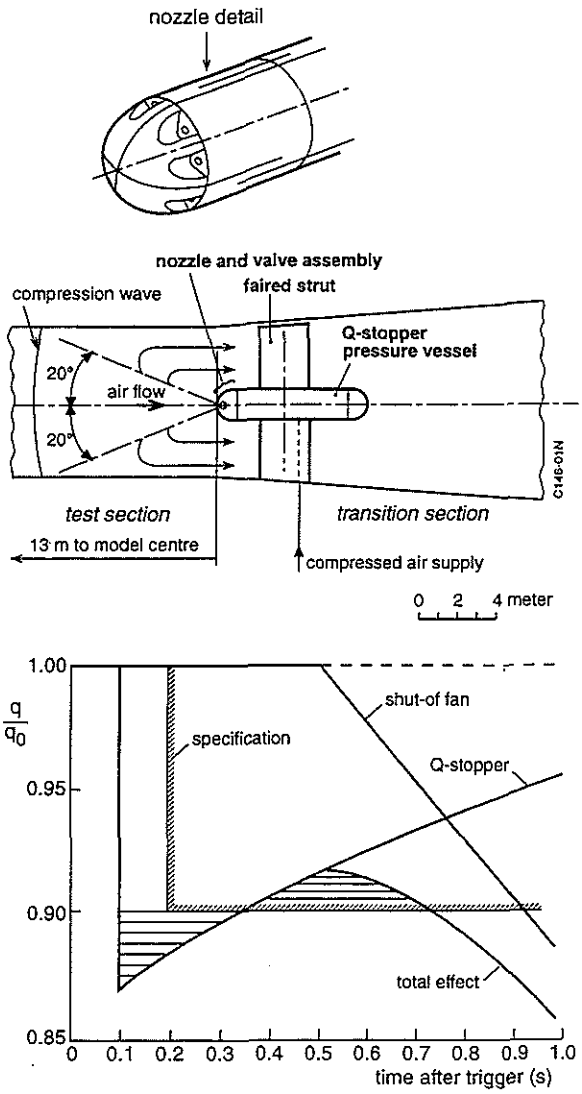


Fig. 11 Q-stopper design for DNW

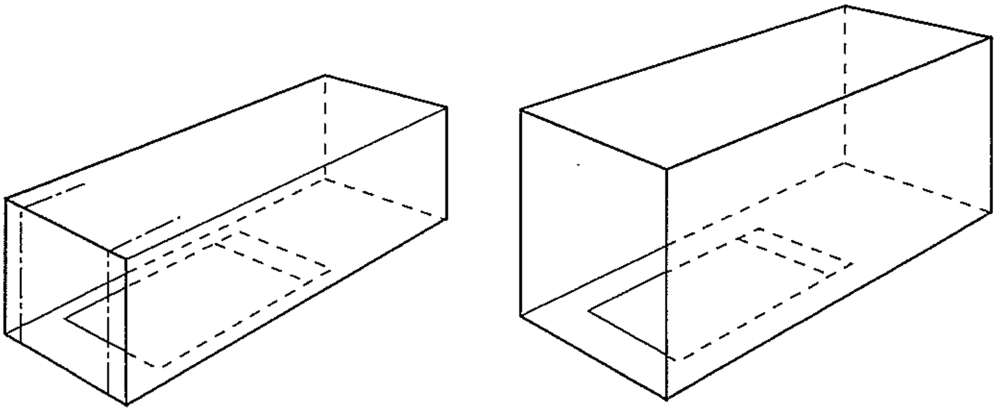
the DLR MUK have shown that the q value can be reduced 10% or more within 0,2 seconds after trigger. Jet braking is only required for a few seconds when simultaneously the fan drive is turned of as well. However the q-stopper has not been realized yet because no use has shown up so far, but the interfaces with the first part of the test section diffuser have been included.

All four walls of the 8 x 6 and 6 x 6 test sections of the DNW are equipped with remotely adjustable slots (max. 12% open) at a pitch of 1 m in order to reduce wall interference. This provision was made in the seventies because it was assumed at that time that within the foreseeable future methods will become available to assess the residual wall interference. Although it has been demonstrated that the wall interference reduces with a slotted wall, the residual interference is still hard to determine. Therefore the slotted wall arrangement is not much used. Maybe future developments will change this picture. In the 9.5 x 9.5 m DNW test section and in the ILST provisions for a slotted wall arrangements are made, but not yet realized and it is felt that this was a good decision. Work is still going on in a joint effort at NLR, DNW and DLR to better understand and assess wall interferences with slotted walls. It should be remarked here that slotted walls consume much energy and that special reingestion measures have to be taken to prevent strong axial pressure gradients (and hence buoyancy) in the test section (ref. 2).

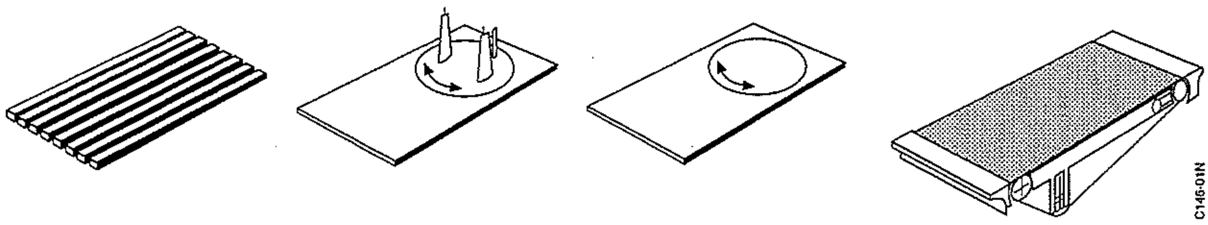
In the DNW test sections, the floors can be interchanged with a variety of floor hatches containing either turntables, slotted wall arrangement or a (moving) ground board provision for ground proximity testing (see fig. 12). In the smaller and less complex ILST and LST some of these provisions are fixed to the test section and for exchangeability the entire test section part is exchanged. It is felt after many years of testing experience that it has been a good decision, for reasons of costs and complexity, to provide the (large) DNW with exchangeable hatches and the smaller tunnels with exchangeable test section parts.
In all tunnels provisions are made to install an axial blowing slit for boundary layer energizing in front of a test object when needed. Every low speed wind tunnel should have such a provision. At DNW also boundary layer scooping is used.

5.3 Test section and model logistics

The last paragraph of the former section already refers to test section component exchangeability. To plan a test section, its provisions in and around it and the associated testing hall and related building arrangement, a clear view must be developed on the tunnel usage in the envisaged market segment. For example the predecessor of the DNW at NLR, the LST 8 x 6 was planned initially (late sixties) for V/STOL aircraft development testing. Then environmental issues became a hot item and noise testing at model scale was requested aiming



convertible 8 x 6/6 x 6 test section **9.5 x 9.5 test section**

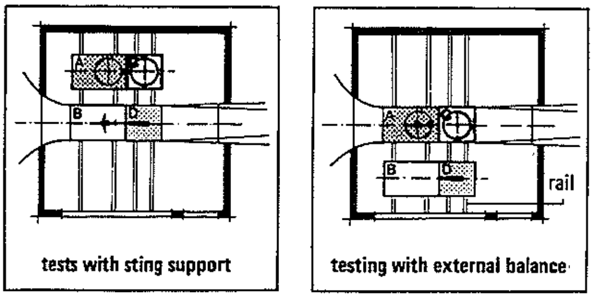


slotted floor section **underfloor balance turntable with struts** **multi-purpose, heavy-duty turntable** **moving belt ground plane** (not in 6 x 6)

Fig. 12 Test section floor interchangeability at DNW for an open test section. The DFVLR (now DLR) brought in high speed helicopter testing giving the 6 x 6 m test section arrangement and full scale component testing asking for the 9.5 x 9.5 m test section. So the DNW was set up for a multi purpose atmospheric test facility with many testing capabilities including extensive propulsion simulation. Studies between a tandem test section arrangement and a exchangeable test section arrangement soon revealed, for aerodynamic (possible flow separations) and productivity (preparation) reasons, that an exchangeable test section arrangement should be preferred. This has the additional advantage that a (removable) model support, can be installed of a fixed location to the foundation.

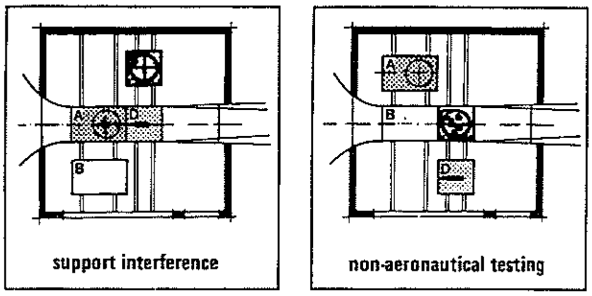
Feasibility studies showed that the 8 x 6 m and 6 x 6 m test sections could be combined in a single arrangement by moving the sidewalls inward and having at the downstream end the last 6 m hinged forming a steep but short diffuser.

Model tunnel tests further showed that for the open 8 x 6 m test section, the 13 m long 9.5 x 9.5 m transition piece to the test section diffuser could be used as a flow collector for the open 8 x 6 m test section arrangement. In total this required 6 pieces to be interchanged (2 movable contractions, 2 test sections, 2 transition pieces with the diffuser). Having this interchangeability done by a rail system, would require a complex system, huge halls and would give little flexibility. This was the reason why a transport system based on aircushions was selected. Although it was risky at that time for such large and heavy applications, the system has shown its value in practice. The (concrete) floor should be very flat, horizontal and air tight (cracks may cause problems because air pressure then penetrates the concrete and may separate layers). The same transport system was selected for the LST. The selected ILST test section arrangement could be easily handled by a rail system and to ensure trouble free operations this system was selected in Indonesia (fig. 13).



tests with sting support

testing with external balance



support interference

non-aeronautical testing

Fig. 13 Possible test section arrangements at ILST

Model entry into the test sections is relatively easy for exchangeable test sections either from downstream or from upstream. This can also be done when the test section to be used is in situ in the circuit by removing the adjacent component (e.g. the contraction at the DNW).

Whereas the model supports of the DNW are fixed to the foundation, at the LST and ILST these devices are fixed to a particular test section component. This gives the advantage at DNW to use the model support for any test section and also in the open test section arrangement. This requirement was not present at the other two smaller tunnels having both a single test section size. To this end at both tunnels the test section is split in an upstream and downstream part and at both tunnels the upstream part is executed in two configurations of which one configuration carries an external six component balance (see fig. 14a) on top of the turntable in the ceiling. The other upstream test section part of the LST contains a set of turntables in the ceiling and floor (for 2-D testing for example) and at the ILST this is simply an empty box. At ILST the downstream end is also executed in two fold of which one part carries a sting support mechanism (see fig. 14b) and the other part a turntable for industrial testing, similar as at the LST. So at the ILST by combining the two upstream and two downstream parts four test section configurations can be made for particular test purposes (see fig. 13).

At both DNW and ILST two model preparation rooms are available. Models can than be brought into the test section at DNW with the use of a movable (on aircushions) elevator. For the ILST an overhead crane is used either when these test sections are in situ or removed from the circuit. At the LST the test section parts can be moved in front of a workshop at the same floor level for easy model preparation, mounting and check-out prior to movement into the circuit. From experiences these three systems for model preparation, mounting and check-out are satisfactory for efficient use.

5.4 Model supports

All three tunnels have an external 6-component balance and a sting support mechanism for model support via an internal balance.

For multi-use requirements the DNW external balance is a floor balance (fig. 15). Although easy for use for floor mounted half models and full-scale cars and trucks the support of full airplane models is cumbersome because only strut supports can be used. In particular the tail strut (and especially the wind shield thereof) gives a

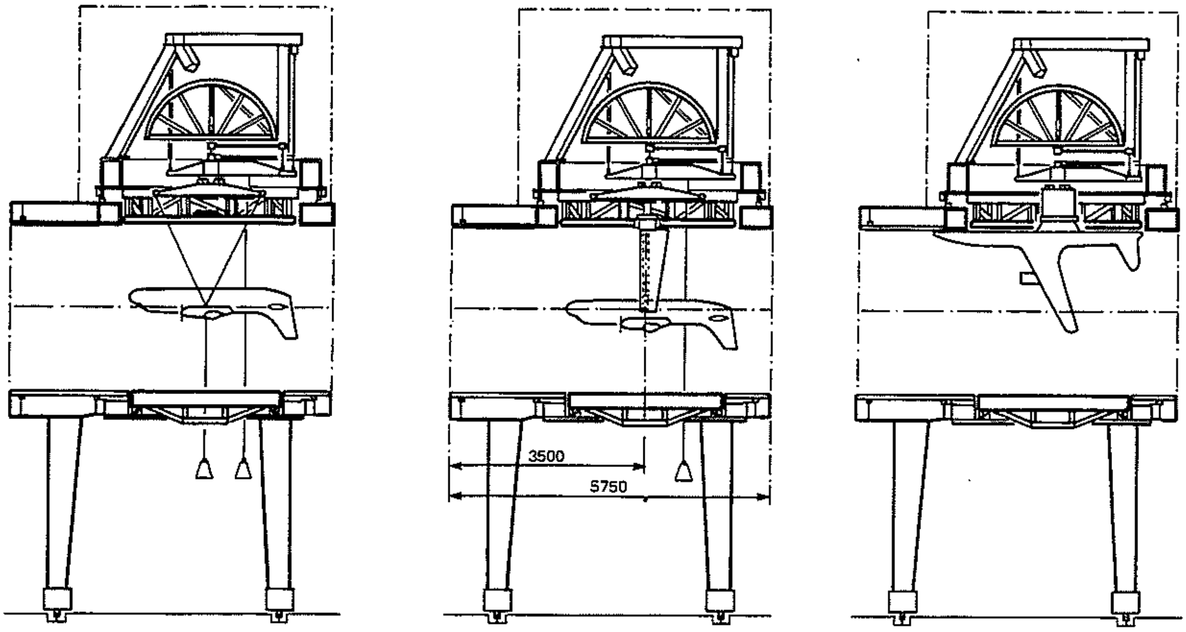
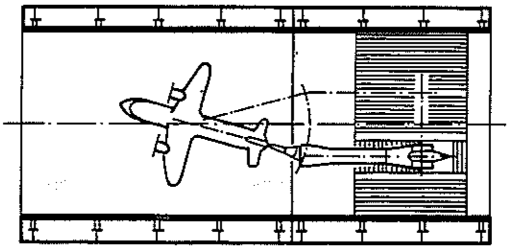


Fig. 14a ILST upstream test section part with external balance

Top view



Side view

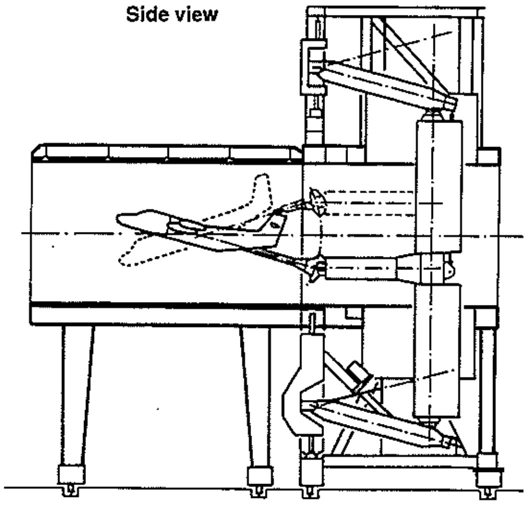


Fig. 14b ILST test section configuration with sting support mechanism

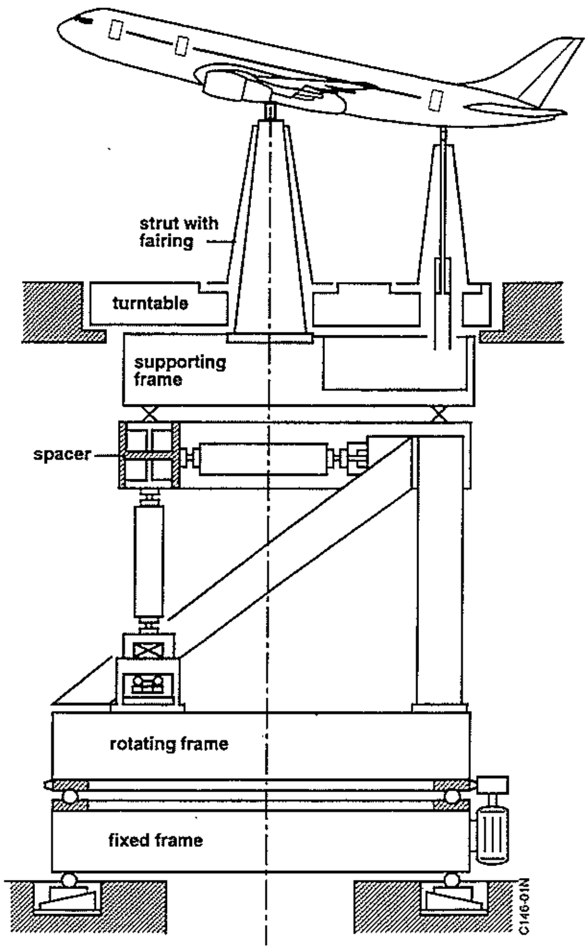


Fig. 15 External balance of DNW with a model supported by struts

substantial aerodynamic interference. Since the test section and the external balance are essentially uncoupled (both separately fixed to the foundation) the yaw and pitch movements have to be carefully synchronized. Since the external balance can be moved on aircushions as well, the balance can be calibrated in a special calibration hall, assuring that the (usually long-lasting) calibration process does not interfere with wind tunnel tests.

The LST and ILST have a similar overhead balance allowing both strut (wing and central) and wire suspension (see fig. 14a). Although wire suspension does not give accurate drag data, the other aerodynamic interferences are minimal and therefore it gives a good basis for interference free testing with the other model support systems. Pitching can be done either bij a pre-loaded pitching wire or by an internal pitch mechanism. Both at ILST and LST the external balances showed to be real work horses and proved to be very stable in course of time. The external thermal covers and temperature controls of the ILST and DNW balances further improve stability in read-out.

The work horse at DNW is the sting support mechanism (fig. 16). DNW has developed an elaborate method for sting support interference corrections for the various stings (dorsal, tail, ventral). The DNW sting support mechanism consists of a streamlined strut, that can move up and down on vertical rails in a 14 m deep pit. This strut supports an articulated boom for yaw and incidence movements. As a consequence the center of rotation moves back and forward. Because all movements are independent the system can also be used to position models just above the moving belt ground plane at the floor level. All movements are powered hydraulically and in the early phase it was problematic to take-over from. the stationary brake position to live hydraulic power control without shaking the model and hence possibly damaging the balance. Now this phenomenon is well under control.
This last phenomon was the main reason to select for the ILST an electromechanic drive and control and besides to have for pitch and yaw each only one single drive. By linkages and torsion tubes it was possible to transfer external movements to the sting movements such that the center of rotation remains at place. The vertical strut is moving laterally when yawing the model keeping the boom in flow direction (fig. 14b). This requires the use of rolling doors in the ceiling and floor of the downstream test section. The boom is relatively of similar size as the DNW boom that so it may be expected that interference effects are similar as well. Although it was planned to execute an extensive support/sting interference exercise in the ILST, this has not been done yet and LAGG (the ILST owner) mainly uses the external balance with strut supports, applying now and then a wire suspension for baseline data.

Recently the LST was equipped with a simple sting support mechanism by placing a segment pitch mechanism in the upstream turntable (fig. 17). From studies at DNW it was concluded that for models of transport aircraft, use of ventral stings is a good solution, for interference reasons, often better than tail stings. The LST sting support mechanism can be easily combined with ventral stings giving a good and cheap solution. However not much experience is available yet.

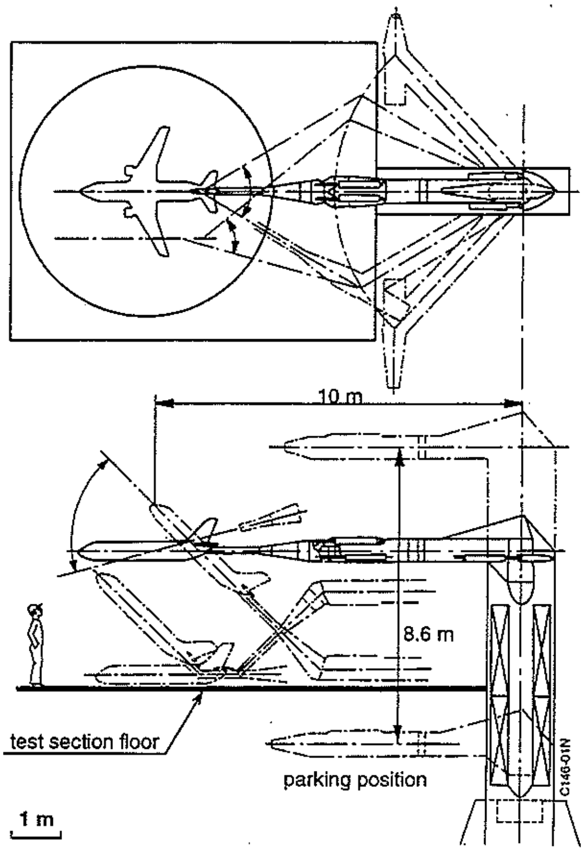


Fig. 16 Sting support mechanism of DNW

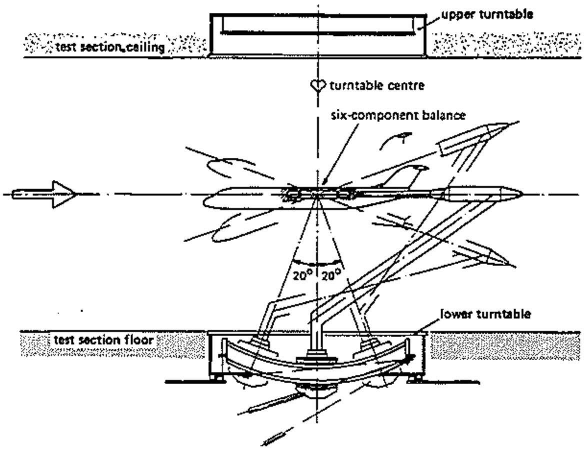


Fig. 17 Sting support mechanism of LST

6. CONCLUDING REMARKS

It has been tried to give an overview of the experiences gained since the mid seventies during the realization, and operation of three low speed wind tunnels in which NLR was strongly involved. Some explanations and backgrounds have been given on aerodynamics and operational issues and where possible experiences and recommendations stated. A selection has been made of topics without going into depth nor having the pretention of being complete. The following general conclusions can be drawn from the above:

- The airline.as developed at NLR is a conservative but solid basis for subsonic wind tunnels giving data which are close to what the aerospace industry is aiming for. Of course further refinements will always be possible and certainly will come up in the symposium where this paper will be presented.
- It is wise to design a low speed facility for multipurpose use. It is difficult to predict which testing capability will ultimately make the tunnel successful in operation and this will change in time. For example the aero-acoustic testing capability is one of the high- lights of DNW. The car industries used this facility extensively until they built their own facilities. Who would have thought that full scale truck testing would be a major application of the 9.5 x 9.5 m test section of the DNW?
- Great care must be devoted to the manufacture and installation of the inserts in the settling chamber. Almost non measureable deviations to the ideal screen properties have measureable effects on the flow angularity.
- It is believed that the sequence and relative distance of the inserts on the settling chamber as described in this paper contribute to high flow quality.
- More theoretical and experimental work should be done to better understand whether and how secondary flows in the contraction may effect the flow in the test section and which improvements may be useful.
- Tunnel operators and users have a tendency to stick to a model support system in which they have gained confidence by building up a data base. This is the case at DNW for the sting support system whereas in Indonesia the external balance is primarily used.
- Little has been said herein on the open test section of the DNW, because in a subsequent paper this item will be treated extensively.

Acknowledgement

Realisation of a wind tunnel is a matter of team work with colleagues and external consultants and contractors. The author feels grateful to have worked with so many of them in various teams in always a very enthusiastic atmosphere. For the writing of this paper the author wants to thank Messrs. van Ditshuizen and Eckert for submission of some old unpublished DNW material and Mr. Ross and the LAGG stafmembers for their inputs on ILST operation experiences.

REFERENCES

1. J.C.A. van Ditshuizen "Design and Calibration of the 1/10th scale Model of the NLR Low Speed Wind Tunnel LST 8 x 6", NLR MP 75031 U, 1975.
2. J.C.A. van Ditshuizen and R. Ross "Aerodynamic and Aeroacoustic Design Aspects" Design, Manufacturing Calibration of the German-Dutch Windtunnel (DNW) CONSTRUCTION BOOK 1976-1980 (Published by DNW).
3. F. Jaarsma and M. Laihad "Indonesian Low Speed Tunnel ILST" Paper 19 of the International Symposium on Aeronautical Science and Technology Indonesia - ISASTI, June 1986.
4. F. Steinle and E. Stanewsky "Wind Tunnel Flow Quality and Data Accuracy Requirements" AGARD-AR-184 1982.
5. T. Wolf "Berechnung des Leistungsbedarfs von Underschall- und Transsonik- Windkanälen" Dissertation, Technical University Darmstadt, 1995.
6. Ann "Performance of Conical Diffusers in Incompressible Flow", Engineering Science Data Unit, Ian nr. 73024.
7. T. Wolf "On the Possibilities for Improvement and Modernization of Subsonic Wind Tunnels" AIAA 90-1423, June 1990.
8. I. Zwaaneveld, "Investigation of Sheet Metal Vane Cascades for 90°C Corners with 0,10 and 20% Extension, NLR (formerly NLL) report A1118, 1950 (in Dutch).
9. S.H. Chintamani and R.S. Sawyer, "Experimental Design of Expanding Third Corner for the Boeing Research Aerodynamic Icing Tunnel" AIAA 92-0031, January 1992.
10. G.B. Schubauber and W.G. Spangenberg, "Effect of Screens in Wide-Angle Diffusers" NACA Report 949 1949.
11. J. v.d. Vooren and A. Sanderse, "Finite Difference Calculation of Incompressible Flow through a Straight Channel of Varying Rectangular Cross Sections, with Applications to Low Speed Wind Tunnels" NLR TR 77109 U 1977.
12. G.G. Börger, "Optimierung von Windkanaldüsen für den Unterschallbereich" Zeitschrift Flugwissenschaften 23, pp. 45-50 1975.
13. J.L. Lumley and J.F. McMahon "Reducing Water Tunnel Turbulence by Means of a Honeycomb" Transactions of the ASME Journal of Basic Engineering, Dec. 1967, pp. 764.
14. K.H. Horstmann, A. Quast and G. Redeker, "Flight and Wind Tunnel Investigations on Boundary Layer Transition" Journal of Aircraft 27, 1990.