STANDARDIZED WIND TUNNEL DESIGN AND CONSTRUCTION FOR AERODYNAMIC RESEARCH AND DEVELOPMENT

Prof. Dipl.Ing. Bernd Ewald,
Technical University of Darmstadt

Dr.Ing. Dieter Holzdeppe,
Turbo-Lufttechnik GmbH, Zweibrücken

Dipl.Phys. Dieter Cronauer,
Turbo-Lufttechnik GmbH, Zweibrücken

Peter Waudby-Smith
AIOLOS Engineering Corporation

Abstract

Since the very beginning of aerodynamic research and development the wind tunnel has been the standard and most important tool of the aerodynamicist. The fast and very successful development of numerical methods in fluid dynamics changed the relative role of experiment and theory in fluid dymamics but the wind tunnel is by no means obsolete. So also in the future new wind tunnels will be constructed and used.

In the past the wind tunnel has been sized, designed and constructed as a unique solution for the very special wishes of the customer. This has required a large degree of engineering to be performed, with the consequent engineering costs. Since the most expensive parts of the wind tunnel (drive unit, fan, balance) have been also special designs to individual wishes, the price of the facility has been pushed even higher. In view of the above, the concept of a standardized wind tunnel design should lead to a reduction of overall costs.

The design methods of wind tunnels have reached high standards. So at least for standard low speed tunnels a successful wind tunnel may well be designed without special engineering work like a pilot wind tunnel etc. A critical review of a variety of modern wind tunnels shows that the requirements of the different customers may well be fulfilled with a standard design.

So in cooperation between the Technical University of Darmstadt and Turbo-Lufttechnik GmbH the concept of a standard line of low speed wind tunnel designs with different sizes has been developed. This concept provides universities, research facilities and industrial companies with the opportunity to acquire a wind tunnel with proven quality at reduced cost.

In this paper, principal design features, tunnel sizes and tunnel performance will be outlined and an example for a particular size will be given.

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1. Introduction

Most existing wind tunnels are a result of individual considerations and more or less rationally supported preferences of the owner fed either into his own design office or into the design office of a wind tunnel engineering company. So worldwide nearly no wind tunnel is a true copy of another.

On the other hand for each wind tunnel the engineering work is nearly done from scratch and sometimes the experts of the wind tunnel engineering contractor have to work very hard to get the possibly unexperienced customer away from some prefixed ideas about his new wind tunnel. So the large share of the engineering work in the total cost of a wind tunnel has to be paid again and again for each new tunnel.

The knowledge base for the design of Low Speed Wind Tunnels is highly developed. Even for the design of large tunnels experimental work with a "model tunnel" normally is not necessary. Wind tunnel design based on proven methods is possible without risk. Although different design and fabrication methods are used, often leading to different shapes of the final facility, these differences are usually not due to special requirements from the customer. Rather they arise from the different design practices and fabrication experiences of the wind tunnel designer.

The consequence of this consideration is that the requirements for the majority of new wind tunnels can be fulfilled very well by a standardized design. In some cases the fabrication of a standardized tunnel design may be slightly more expensive than a tunnel tailored for a very specific task, but this is by far compensated for by the large savings due to reduced engineering effort. Since the available engineering capacity of wind tunnel design experts may be concentrated on some standard designs, these standard designs may be engineered much more carefully. Additional large savings are possible in the tunnel fabrication by using identical parts for tunnels of different size, as shown in the paper.

An additional advantage for the client is the very detailed and precise information on what he is going to order with the possibility to examine the tunnel in reality, may be in a scaled version.

2. Standard Design of Air Line

About twenty years ago the DNW was designed and this excellent wind tunnel set something like a design standard for modern wind tunnel airlines. The Indonesian Low Speed Tunnel and the new NLR LST closely followed the design rules established by the DNW.

2.1 Design Features of Wind Tunnels like DNW

- Slender diffusors with diffusor angle not exceeding ca. 4° for the high speed diffusor and 5° for the main diffusor.
- Wide angle diffusor in front of the settling chamber with loss elements to prevent separation (i.e. screen and/or heat exchanger)
- Thin turning vanes.
- Careful design of all settling chamber installations (heat exchanger, honeycombs, screens) for optimum flow quality and low loss.
- Careful optimization of nozzle geometry by CFD methods.
- Considerably high contraction ratio for high flow quality.
- Sophisticated fan design for high efficiency and quiet operation. Aeroacoustics has become an important field of wind tunnel research, so quiet operation is a requirement for a modern tunnel design.
- Aeroacoustic treatment.

The wind tunnels which were built following the DNW standard are very successful and demonstrate high flow quality and high energy ratio. Since today even for small wind tunnels drive energy is an important part of the operating costs, the design for high energy efficiency is mandatory.

2.2 Design Features of the Standardized Wind Tunnel

Figure 1 shows the standardized wind tunnel air circuit design, which is a slightly modified version of the DNW standard. Driven by the ratio of 4 : 3 of width to height of the test section, all cross sections of the wind tunnel are designed to this ratio. Test section length is 2.5 x the hydraulic diameter. Both high speed diffusor and low speed diffusor have the same area ratio of 2 and the same opening angle of 5 °. For cost effective construction the cross legs have constant area.

In Figure 2 the wind tunnel components are numbered. The drawing shows, that the first and second corners, the third and fourth corners, the transition pieces (12) and (14) of the fan and the components (11) and (15) are identical. The test section diffusor (10) and the fan diffusor have identical geometries scaled by a factor of $\sqrt{2}$.

The equally spaced turning vanes are circular 90° arcs with extended leading and trailing edge according to Ref. [1]. The geometry of the corners is identical for all sizes, so is the number of vanes for all corners.

The area ratio of the wide angle diffusor (6) is 2. A screen is mounted in the wide angle diffusor to prevent separation. At the entry of the settling chamber an optional heat exchanger can be placed to keep test section temperature constant. Sufficient cooling may be achieved with less effort by an optional air exchange system. The heat exchanger may also be designed as a cooled flow straightener. Note that if a heat exchanger is not used a screen is required to ensure proven operation of the wide angle diffuser. Downstream of the heat exchanger a set of turbulence screens is mounted. The number of screens used is a compromise between cost for the screens, fan power and the individually specified turbulence level in the test section. The nozzle is designed and optimized for flow quality and length by numerical computation.

The wind tunnel shown in Figure 1 has a closed test section, since this configuration is the widely accepted state of the art in wind tunnel testing. Nevertheless the same basic air circuit design may be used with an open or slotted test section.

3. Scaled Wind Tunnel Series

To get the full advantage from the idea of the standardized wind tunnel design, a full series of wind tunnel sizes must be defined. An appropriate scaling of the tunnels offers additional possibilities for cost reduction. The basic idea is to scale all length dimensions by $\sqrt{2}$ for the next larger or the next smaller tunnel size. So the next larger tunnel has twice the test section area.

This scaling results in large cost reductions for the tunnel workshop drawings and the tunnel fabrication. A given tunnel and the next larger one has several identical parts. The fan diffusor is the test section diffusor for the next larger tunnel. The large corners (3,4) are identical to the small corners (1,2) of the next larger tunnel.

Figure 3 shows a full range of wind tunnels for the test section areas 0.375 m^2 up to 6.0 m^2, which covers the range from a small research tunnel up to a large university wind tunnel or a medium size industrial tunnel.

4. Wind Tunnel Drive

All wind tunnels are driven by a single stage axial fan with fixed pitch rotor blades (pitch adjustable at rest) and a variable speed motor installed in the hub. All fan designs are geometrically similar; the fans are also scaled by a factor of $\sqrt{2}$. Each fan is available with two different motor sizes; the small one offers a maximum tunnel speed of about 70 m/s. The large motor has twice the power and offers a maximum tunnel speed of about 90 m/s. With the large motor the installation of a water cooler in the settling chamber is mandatory.

5. Wind Tunnel Circuit Installations

The design of the corner vanes has been already mentioned in chapter 2. A debris catch screen is installed upstream of the fan.

To prevent large scale flow separations along the length of the wide angle diffuser a screen will be required. Positioning and loss factor k has been chosen according to Ref. [2] taking the pressure loss of the downstream heat exchanger into account.

The heat exchanger will be a two row design with a local pressure factor of about k = 2.5.

Downstream of the heat exchanger a honeycomb flow straightener will be installed. There is some discussion about the optimum sizing of this item. According to Ref. [39] we have chosen a length over hydraulic diameter ratio of the cells of $L_H/d_{hydr\,H} = 15$.

Turbulence reducing screens with a local loss factor of about k = 1 (Ref. [2],[4]) will be used with their spacing based on two factors. First, the distance between two screens has to allow for the decay of the screen induced turbulence. The second is that there should be enough space between all the screens so that they can be easily cleaned. This is also true for the other flow conditioning devices. The distance between the last screen and the contraction inlet is constrained by two mechanisms. A small boundary layer growth on the walls requires a small distance. On the other hand the upstream influence of the contraction should not reach the final screen.

The determining criteria for the number of turbulence screens will be the flow quality (turbulence levels) in the test section. This is an aspect to be discussed with the individual customer, suited to their testing needs.

6. Design

For the fabrication of the wind tunnel three materials (steel, wood, concrete) are typically used. Each of these materials has its specific advantages and disadvantages.

Steel components can be manufactured world wide in a sufficiently good quality. Furthermore there are no climatic constraints as long as steel is treated with anti corrosion coatings.

Wood and concrete are the preferred materials for aeroacoustic wind tunnels, since the poor noise conduction of these materials aids in minimizing structure-borne noise. In contrast, a steel structure requires special care to avoid structure-borne noise contributing significantly to the test section background noise levels.

In the past, wood has been the prime material for smaller university wind tunnels owing to the simpler fabrication requirements and modification possibilities of wood.

Modern concrete techniques allow for good manufacturing tolerances. Some large aerodynamic facilities e.g. DNW, Porsche LWST and Indonesian Low Speed Tunnel have been completed very successfully using concrete.

Concerning flow quality there is no difference between the three materials. Recent price investigations have shown that the steel type and wooden type wind tunnels are comparable in costs. For the large wind tunnels selecting steel or concrete would be on a case to case choice based on local market conditions.

In this paper we have selected a standard welded steel design with stiffeners.

The components either can be welded together or can be connected by bolted flanges. Taking cost aspects into account we have chosen the welding technique. The wall thickness will be 8 mm for the largest tunnel and 5 mm for the smallest one. The loads on the wind tunnel structure would allow thinner steels to be used but welding becomes more difficult. As a result a distortion of shape could happen, and the manufacturing tolerances could not be met.

From the test section downstream to the transition in front of the fan diffuser, spacing and size of the shell stiffeners is the same. For the rest of the components the stiffeners are sized with the factor of $\sqrt{2}$ according to the wind tunnel series. This ensures easy up- or down-scaling.

The wind tunnel support structure consists of three different types of struts. So called fixed struts are mounted to the transitions upstream and downstream of the fan. Nozzle and test section diffuser inlet
are also fixed. The achievement is that the test section does not move, which is for instance important because of the balance. The struts assembled to the corners are flexible to allow thermal expansions. To carry the settling chamber loads while allowing thermal expansion sliding blocks are foreseen.

The fan is mounted on a concrete block which is fixed to the foundation with spring elements. The shell of the fan section is connected to the tunnel shell with elastic compensators. By this a complete dynamical decoupling of the fan and the wind tunnel shell is accomplished.

For withstanding the operational loads in the two largest facilities of the wind tunnel series, the turning vanes have been horizontally splitted. For aerodynamic and cost reasons this method is better than increasing the turning vane thickness. For all of the wind tunnels we have selected a material thickness of 5 mm for the vanes.

In accordance with a successful design realized some years ago for the modernization of the Darmstadt University Low Speed Wind Tunnel the corner vanes can also be fabricated with glass fiber reinforced plastics.

The turbulence screens will be mounted prestressed in special devices. Special care is focused on the design of these mountings including those for the flow straightener and the heat exchanger, so that the flow will not been disturbed.

7. Instrumentation

The instrumentation and especially the data acquisition and evaluation software offers a large cost saving potential as well.

In the past the standard wind tunnel instrumentation was based on minicomputers like MicroVax or similar machines. These were linked to the data acquisition hardware by different interfaces.

The rapid development of the Personal Computer changed this situation completely. A modern PC based on a 486 processor is well qualified as a main computer for wind tunnel control and data acquisiton. Even in the case of a large wind tunnel a network of two to four Personal Computers is well qualified for the tasks of tunnel control and data acquisiton. For the small to medium size wind tunnels demonstrated in this paper a single PC provides enough control and evaluation power.

For the standardized wind tunnel series we propose two instrumentation solutions; a low cost solution for small tunnels and a professional solution for higher and more professional demands.

1. Low Cost Solution

A 486 PC is proposed with a multi channel measuring card for measuring data acquisition and a digital I/O card for tunnel control.

The measuring card shall have programmable preamplifiers for low level signals and a minimum of 12 bit resolution. A printer is provided for result documentation and a plotter for presentation of the results in diagrammes.

An additional IEEE bus interface allows the connection of additional measuring hardware.

2. Professional Solution

Also in this case a 486 PC is provided with higher speed and a large hard disc. This PC has a digital I/O card for tunnel control and an IEEE interface for the measuring hardware.

For the data acquisition one or several Digital Measuring Computers DMC 9012 from the Hottinger Company are connected to the PC. This equipment allows the use of different measuring inserts. The measuring inserts offer high precision measuring channels for DC signals, AC signals, thermocouple signals etc. This type of measuring equipment is used with excellent results in the wind tunnel of the Technical University of Darmstadt.

The IEEE interface allows the connection of additional measuring equipment like pressure scanners etc. Standardized software allows the usual wind tunnel data evaluation.

8. Performance

8.1 Flow Quality

There are a couple of parameters to characterize the flow in a wind tunnel. For illustration we have selected the turbulence in the test section as being well understood and accepted for this purpose.

For estimating turbulence levels, experimental results from the DNW facility (Ref.5) and the Volvo Aerodynamic Wind Tunnel (Ref. 6), nozzle exit data) have been used as the basis, with adjustments made to account for contraction ratio and number of screens according to Ref. (7). These turbulence values indicate the effect of the number of screens on the test section turbulence levels and fan power requirements.

Table 1 shows lateral and axial turbulence levels and required fan power, as a function of screen number.

The power estimates were made for the wind tunnel with the 6 m2 test section cross section area. Further, a speed of 90 m/s and model loss of a typical model (5 % blockage) were assumed.

8.2 Acoustic Performance

The facility as decribed in the earlier chapters can be easily converted into an open jet test section which is the preferred configuration for acoustic measurements.

Table 2 gives some predicted performance values for the sound pressure levels for the 'In and Out Flow'- case in the open jet test section.

The above mentioned values assume fiber-filled perforated covering of cross leg 1 and 2, test section diffuser, and fan section. The thin turning vanes are converted into foam covered profiles. Additionally the plenum is completely covered by fibre wedges to assure free field conditions.

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Table 1: Axial and lateral turbulence levels and required fan power as function of screen number

No. of Screens	0	1	2	3	4
Tu_{axial} (%)	0,38	0,19	0,11	0,07	0,05
$Tu_{lateral}$ (%)	0,35	0,19	0,13	0,08	0,06
Fan Power (KW)	1170	1210	1250	1290	1330

Table 2: Predicted sound pressure level in the open test section

Octave Band Center Frequency Hz	In Flow Sound Pressure Level dB	Out Flow Sound Pressure Level dB
63	90	72
125	93	77
250	90	71
500	90	71
1000	87	65
2000	80	61
4000	80	55
8000	80	55
16000	80	55
overall	97,7	79,8

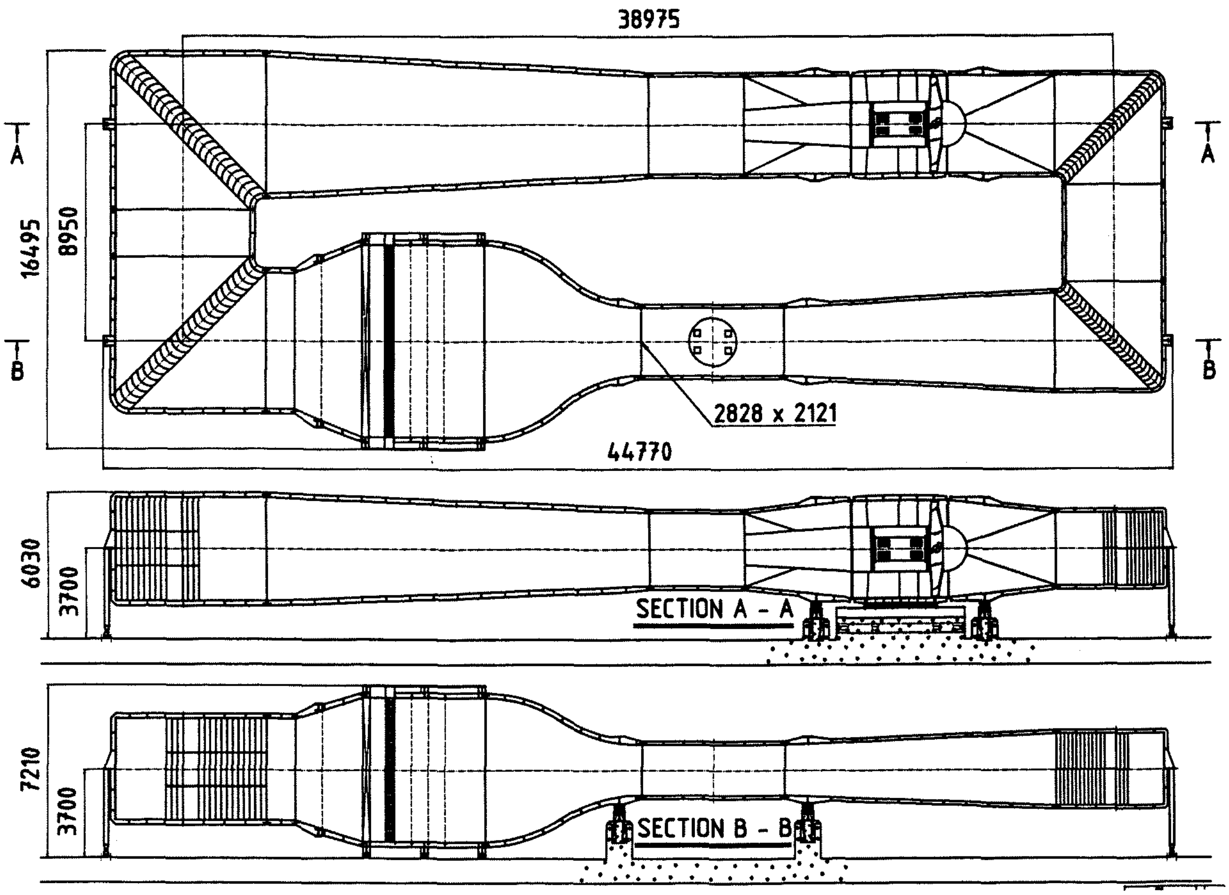

Figure 1. Standardized Wind Tunnel

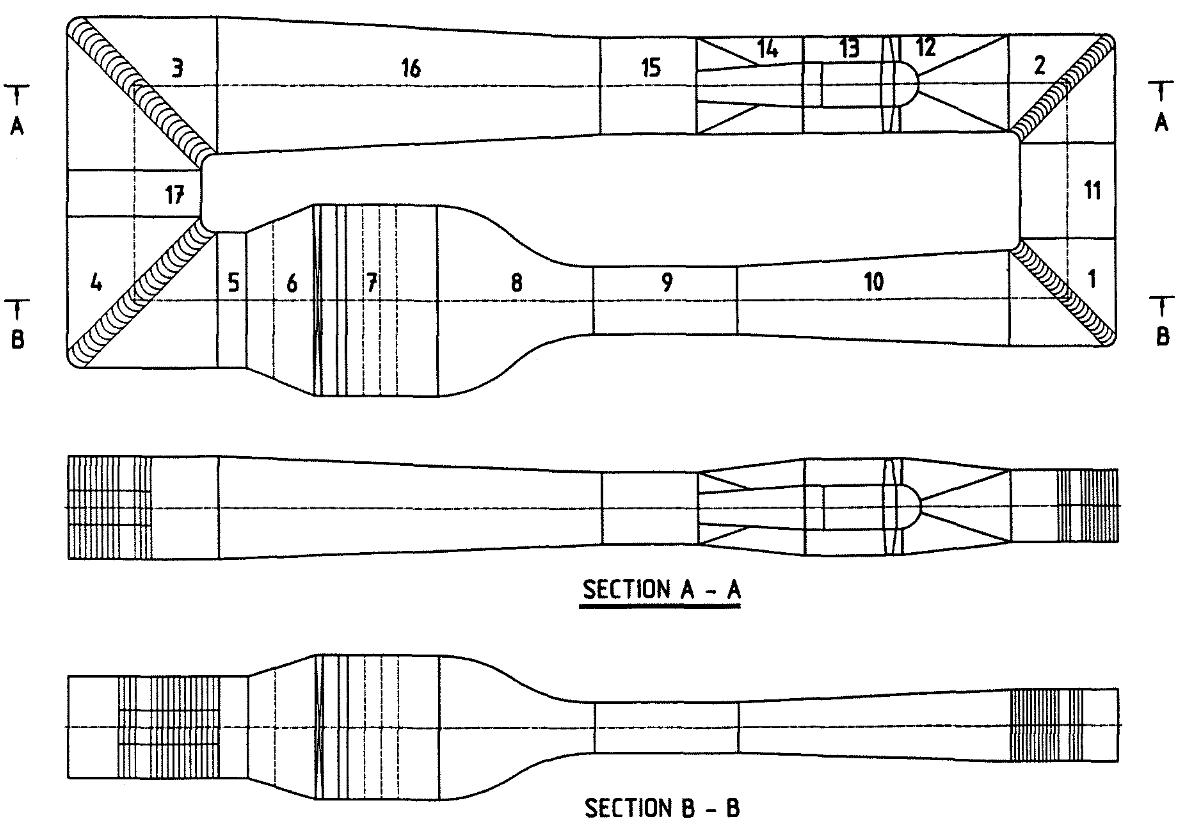

Figure 2. Airline and numbered wind tunnel components

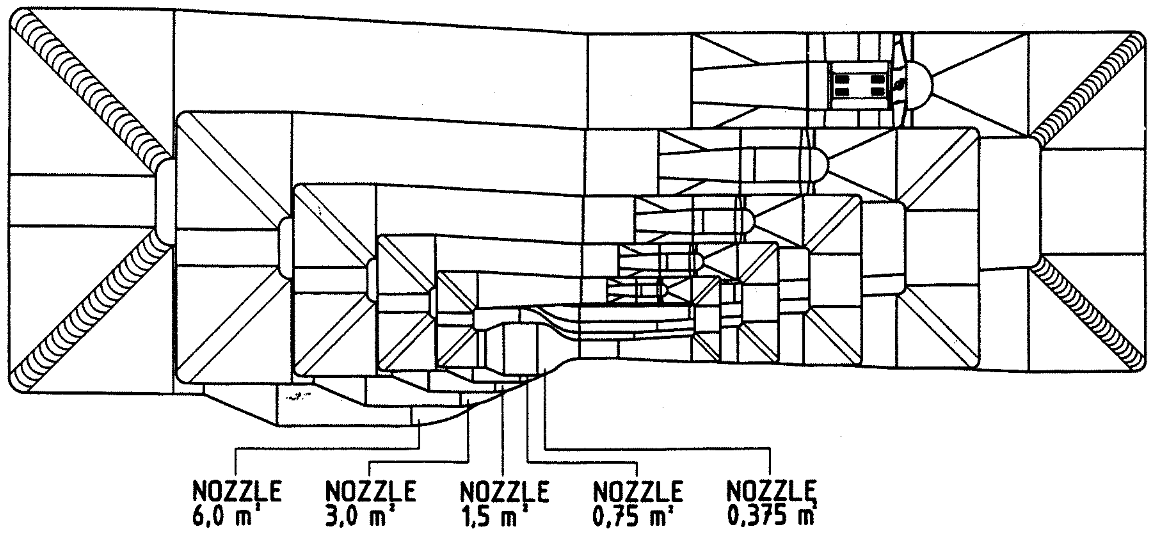

Figure 3. Scaled Wind Tunnel Series