ICAS-96-1.5.1

ETW - FLOW QUALITY ASPECTS AND FIRST MODEL TESTS

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Abstract

This paper presents results of the 2nd phase of the aerodynamic calibration and flow quality assessment as well as force measurements performed with the ETW Reference Model. A brief description of the facility and its unique aspects is included.

Running up to 55 millions tunnel Reynolds number, surveys in the model volume demonstrate the excellent homogeneity of temperature and pressure. The achieved noise levels in the test-section confirm the existence of a quiet transonic windtunnel.

Force and moment tests on a model show that a level of data quality has been achieved which allows to produce a repeatability in drag of 1 count. This goes along with a high productivity rate which is now essential for a commercial facility.

Introduction

The construction of the European Transonic Windtunnel, a facility being designed to satisfy the increased requirements of the aircraft industry, was started in 1988. Mechanical completion was declared by the end of 1992 with a progressive overlap of commissioning and calibration tasks. Shake down tests and preliminary calibration were performed in the period from beginning of 1993 to mid of 1994. Due to existing restrictions on the injection system and the philosophy to start tunnel operations with moderate loading, the transonic operating envelope was covered only up to pressures of 400 kPa and minimum temperatures of 147 K only. These very promising early achievements are reported in (1).

During 1995 some of the European aircraft constructors have helped ETW by providing models for testing to develop the operation of the tunnel. Main target was to experience flight Reynolds number testing and to compare results with known characteristics of aircraft already in service.

Mid of 1995, during the maintenance campaign, the 230 injection nozzle actuators were modified to be fully suitable for low temperature and simultaneous high pressure operation.

Facility Description

ETW is located in Germany in the vicinity of the Cologne/Bonn airport and one of its mother establishments, the German aerospace and research centre DLR. An aerial view of the ETW site as it looks today is presented in figure 1.

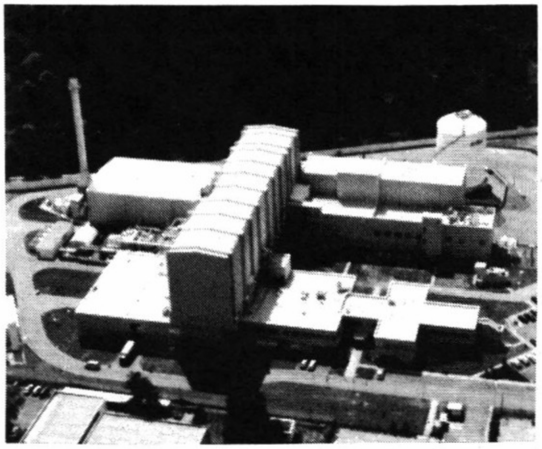

Fig.1 Aerial view of ETW

The dominating elements are the windtunnel building, the vent stack and the high transfer hall which links the model preparation area, model conditioning rooms and tunnel.

The actual performance capability is a Mach number range of 0.15 to 1.3, pressure range of 110 to 450 kPa and temperature range from 100 to 313 K. This allows ETW to generate maximum Reynolds numbers of around 60 millions at a Mach number of 0.95 based on a chord length of 0.219 meters (tunnel chord).

As the facility can only be operated in nitrogen mode, a sufficient quantity of liquid nitrogen is supplied by the 4000 cubicmeter storage tank which is filled from mobile truck units.

The aerodynamic lines of the tunnel are shown in figure 2 stating the overall dimensions by 62m x 11m. To provide high flow quality in the test volume, the settling chamber with its two anti-turbulence screens and a honeycomb flow straightener is preceeded by a wide angle diffuser containing two filling screens.

The test-section of 2.4 m x 2 m is slotted and the amount of ventilation can be varied during a shut-down period by replacement of inserts in all four walls. Presently the side walls are solid and by slotted floor and ceiling an overall ventilation ratio of 3.4 % is provided.

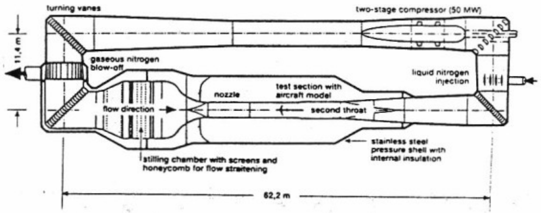

Fig. 2 ETW airline

Supersonic flow is achieved in the test-section by a flexible adjustable nozzle. For high dynamic flow quality a second throat can be choked downstream of the test-section to prevent upstream propagation of noise and turbulence.

The primary design goal of ETW was to provide a highly productive tunnel in a cost effective manner with a maximum of confidentiality during client testing. As facility cooldown procedures are time consuming and use large amounts of nitrogen and electrical power, it is obvious to strive for a system which allows fast and easy access to the models and takes the benefit of being able to test different models at cryogenic tunnel conditions in an interleaving test mode. A satisfying solution was realized with the ETW model cart concept. The two model carts, which are presently available, consist of the test - section ceiling, the sector including the forged sting - boss and test assembly. Taking into account the backup structure of the cart and the instrumentation cabin on top, which is permanently accessible during a test, the total weight of the component comes up to about 200 tons.

The whole sequence from model delivery up to the final performance of a test in the tunnel can be impressively demonstrated by figure 3.

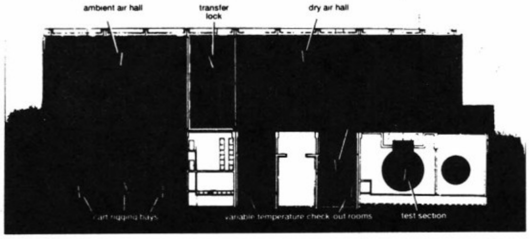

Fig. 3 Section through transfer hall

Client models are received in the model preparation rooms which are individually linked to a cart rigging bay (CRB). Here the models will be assembled and attached to the building jig, a support system capable of full range pitch and roll motions. When the model cart is available, the test assembly is moved to the CRB and mounted on the sting - boss of the cart. After the completion of the instrumentation services the model can be checked out and data acquisition can be operated fom the adjacent individual user room.

Following the completion of the model, the model cart will be picked up and lifted by the model cart transporter to be moved into the transfer lock which separates the ambient from the dry air area. After a satisfactory reduction of the humidity the transport to the test - section can proceed or the cart may be lowered into a variable temperature conditioning room (VTCR). The capability to generate here typical tunnel temperature levels allows for final checks of the equipment or a dead weight calibration under cryogenic environmental conditions.

The VTCRs are also used to park the model cart during interleaving tests with different carts at similar conditions or to perform checks, repair work, or small configuration changes on a model.

More detailed information about the facility and its operation is given in $^{(1-3)}$.

Calibration and Flow Quality Assessment

During the first calibration phase extensive experimental investigations have been performed up to Reynolds numbers of 30 millions. Results are presented in (1). Figure 4 shows that today the designed subsonic/transonic operating envelope of the tunnel is fully explored and even exceeded.

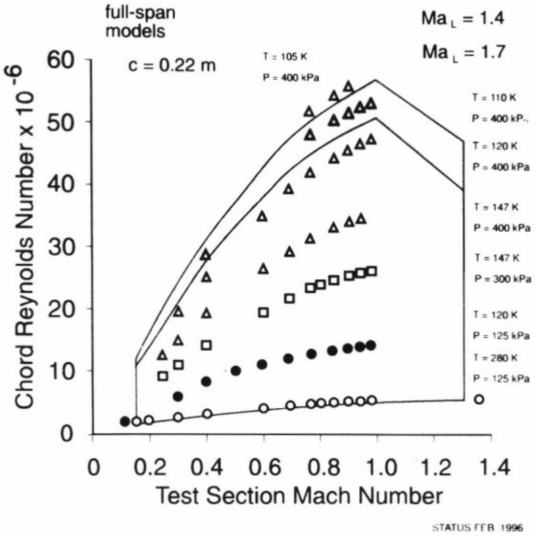

Fig. 4 Covered operating envelope

No restrictions on operability were detected, and trials to achieve Mach numbers below 0.20 required to perform testing of aircraft landing configurations showed very promising results.

Temperature Distribution

Nitrogen is injected into the tunnel through 230 nozzles being individually controlled to maintain a homogeneous temperature across the test-section in all operating conditions. For tuning the injection system, a set of cables was spanned across the downstream part of the settling chamber.

At each node a "premium wire" quality identical batch thermocouple was attached providing a total of 45 measuring points. Comparisons with measurements in the model volume using a rotating rake did prove that the demanding specification of a constant temperature within 0.25 K is met. After the modification of the injection nozzles mentioned above, the temperature homogeneity had to be rechecked and also confirmed for Reynolds numbers above 30 millions. An example measured in the settling chamber for Re_t = 44 millions is shown in figure 5. Taking into account the observed reduction of the inhomogeneity from settling chamber to model volume, the obtained T_{min} = 0.5 K / T_{max} = 0.7 K values result in deviations of about ± 0.25 K in the test - section.

T_t = 120 K
P_t = 400.1 kPa
M = 0.85 ΔTt_{max} = - 0.47 K
Q = 126.2 kPa ΔTt_{min} = 0.7 K
Re_t = 44.03 mio

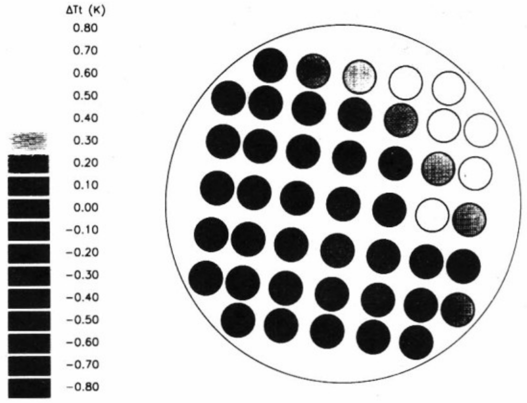

Fig. 5 Temperature homogeneity in the settling chamber

Pressure Uniformity

The total pressure field in the model volume was already analysed during calibration phase 1 based on readings of pitot - probes installed on the rotating rake I. The requirement to gain information about flow angularity as well as dynamic flow behaviour in the test-section led to the entry of the Rotaing Rake II. In comparison to rake I, it is equipped with 7 five-hole probes of the Goodyear type, 2 hot-film and 2 hot -wire probes and 2 Kulite probes for pressure fluctuation measurements (figure 6). While the complex analysis of the unsteady flow is presently not yet completed, the total pressure taken from the central bore of the 5 hole probes is available and gives an indication of the total pressure field at high Reynolds numbers.

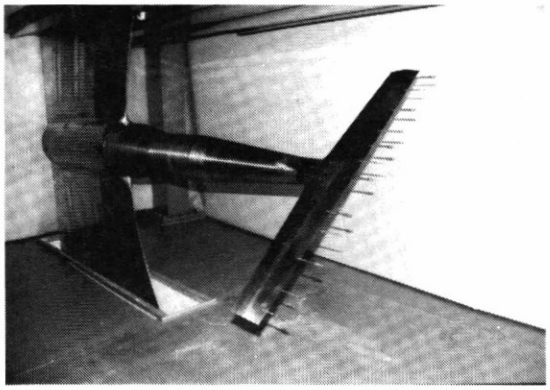

Fig.6 Rotating rake II

The high accuracy provided by small range differential pressure transducers demonstrate a uniformity of better than 0.15 % (i.e. ± 600 Pa) for a typical high Reynolds case of 42 millions generated by a pressure of 400 kPa and a temperature of 120 K at a test Mach number of Ma = 0 .78 as presented in fig. 7.

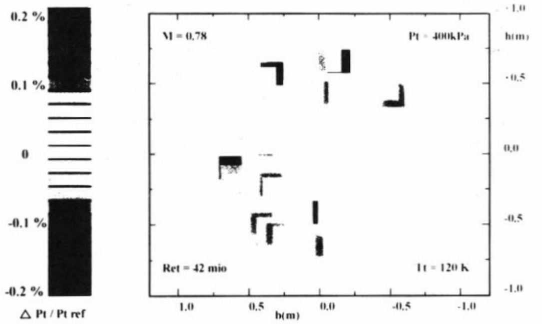

Fig. 7 Total pressure distribution in the model volume

Measurements on the centreline show that no pressure loss referring to the settling chamber was present.

The axial flow uniformity in the model volume is verified by means of pressure tappings on the test-section walls and on centreline axial probes. Setting angles for the top and bottom wall and the reentry finger flaps were already chosen during the first calibration phase. The obtained good axial Mach number distribution could also be achieved at high Reynolds number conditions for the empty test-section (i.e. with the sting-boss retracted from the flow and hidden within the top wall structure).

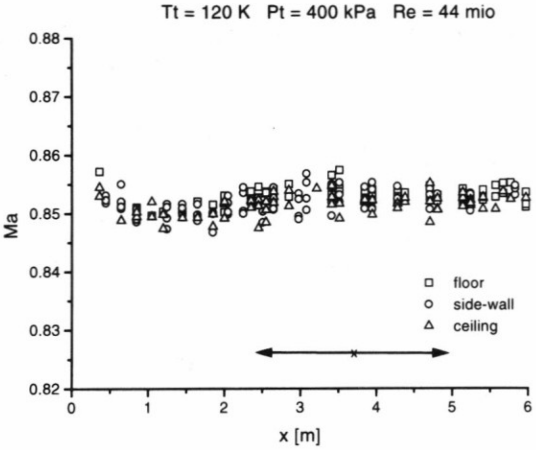

Fig. 8 Wall Mach number distribution for an "empty test-section"

Figure 8 reproduces the axial Mach number distribution on the test-section walls at a Reynolds number of 44 millions. No vertical or lateral gradients could be noticed over the model volume being indicated by the straigth line in the figure. The point of model rotation typically used for transport aircraft testing is represented by the cross.

The individual signature of about 180 pressure taps being considered here is generating a data scatter of M = ± 0.003. It should be pointed out that the scattering is lower at ambient conditions, but running at a pressure of 400 kPa leads to a reduced absolute accuracy of the pressure transducer and the thin boundary layer amplifies the tap signature caused by imperfections of the pressure orifices.

To determine the centreline pressure / Mach number distribution, the short axial probe has been used. This probe is in fact a cylindrical pipe attached to a straight sting, hence, representing accurately the tapered parts of the "ETW Straight Sting". The probe's nose, an ogive, is located about 1.5 meter downstream of the test-section inlet while the beginning of the first taper starts at 4.81 m.

To be able to get the prerequisite for the determination of a very accurate buoyancy drag over the full operating range, maximum care was applied on the machining and surface finishing of the probe and its pressure taps as well as the alignment in the test-section. This did pay out in the capability to minimize the signature of the two rows of pressure taps to a level of less than

± 4 Pa for M = 0.2 at ambient test conditions.
In figure 9 centreline Cp - distributions are given for a Mach number range from 0.4 to 0.98 for high Reynolds number test cases.

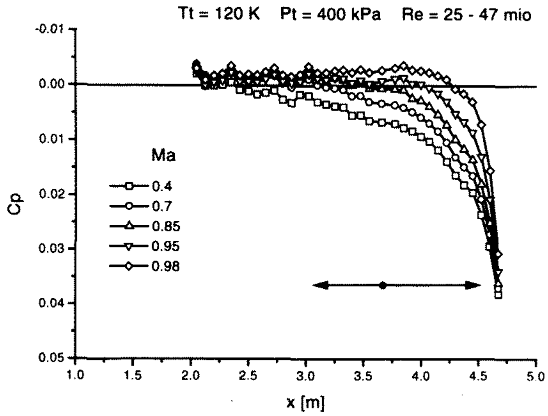

Fig. 9 Pressure distribution on the Short Axial Probe

In the lower part of the figure the length of the ETW Reference Model is indicated with the relevant point of model rotation. The pressure increase due to the beginning of the taper is dominating the pressure field. At the upstream end, the deceleration on the rear part of the probe's nose is just still visible. The largest axial pressure gradient over a model is induced for low Mach numbers being continuously reduced with increasing speed. For M = 0.98, a constant centreline pressure up to about 4m can be stated. Despite of the efforts to achieve excellent surface quality small orifice signatures can still be detected.

Turbulence and Noise

For high Reynolds number testing low fluctuation levels of the aerodynamic quantities are essential for realistic simulations of flight conditions. Here, turbulence and pressure fluctuations are of particular interest and importance. As nowadays the performance of qualified turbulence measurements in cryogenic environment at transonic speeds still means a challenge for the applied technique, it was decided to gain experiences by carrying out at first investigations in the settling chamber. Very promising results have been obtained from the competitive testing with crossed hot-wire and hot-film probes.
Recently the same type of instrumentation was successfully applied in the test-section up to Reynolds numbers of around 40 millions and Mach numbers of 0.9. Data analysis is presently ongoing.

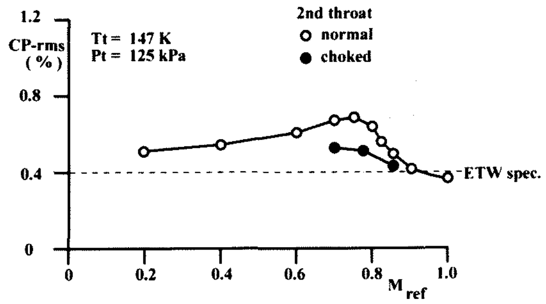

Fig. 10 Pressure fluctuation level in the test-section (with auxiliary grid in the settling chamber)

In parallel, noise measurements with wall and rake mounted Kulite pressure transducers have been performed. Figure 10 shows some results which have been obtained when an auxiliary grid to support temporary instrumentation was still installed in the settling chamber. Here the Cp-rms levels are already very close to the demanding specification value of 0.4 %, especially when taking the beneficial effect of running with the second throat choked.

First Model Tests

The ETW Reference Model

Already during the early design phase of ETW attention was given to the selection of a test-model suitable for cryogenic environment and to be used for research work as well as for periodic checks of data quality. Finally it was decided to build a larger scaled version of the DLR - F4 wing body configuration. It is a typical configuration of a wide-body transonic transport aircraft of the late eighties decade with a wing design Mach number of M = 0.785.
To be representative for the size of aircrafts to be tested in ETW, a wing span to tunnel width ratio of 0.6 was realized which leads to a tunnel blockage of about 1%. The relevant aero-dynamic mean chord is 0.173 m.
An impression how the model finally looks like is provided by figure 11. It is worth to point out that a surface finish of 0.2 µm was required to

achieve the prerequisites for high Reynolds number testing with natural transition. As to be seen, the model is mounted on the ETW Z - sting and attached to a model building jig in the preparation area.

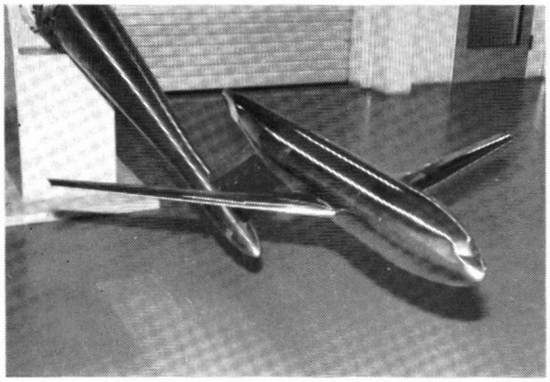

Fig. 11 ETW Reference Model

Effects of Reynolds number

After the facility was declared to be fully operational over the designed Reynolds number range, it was obvious to demonstrate the variation of aerodynamic characteristics such as drag, lift, and moments with Reynolds number. In a first entry the model was operated without any transition fixing up to a Reynolds number of 33.8 millions based on mean aerodynamic chord. This condition was generated with a temperature of 120 K and a tunnel pressure of about 420 kPa. In figure 12 the resulting drag behaviour versus the investigated Reynolds number range is presented for zero lift and a CL = 0.5 (i.e. wing design value).

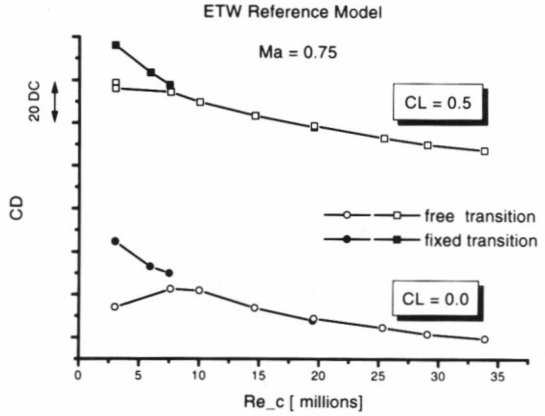

Fig. 12 Variation of drag with Reynolds number

The indicated test conditions were generated at three temperature levels (294 K > Tt > 120 K) selecting the relevant pressures (130 kPa $\leq$ Pt $\leq$ 420 kPa). For Re_c = 19 millions the same test conditions were established with different pressure / temperature settings.

For "free transition" the drag drops in the low Reynolds range. This is due to the existence of large laminar flow areas on the wing which were verified by flow visualization applying the acenaphthene technique. This flow type changes for CL > 0.4.

A set of polars taken at ambient temperature was repeated but this time with a transition fixing on the wings. Using carborandum, its location and the grid size was optimized for a Reynolds number of 3 millions. Consequently, changing the flow behaviour on the wings, it generates an increase in drag by 20 - 30 counts depending on lift. The curves for fixed and free transition seem to merge at a Re_c of about 10 millions.

Comparing the drag level at 3 millions (transition fixed) with the measured drag for Re_c = 33.8 millions, a drop of about 50 counts can be identified.

Results being presented in figure 12 are extracted from typical model test - polars (i.e. pitching the model with a rate of 0.15 deg/sec or operating in pitch / pause mode on clients request).

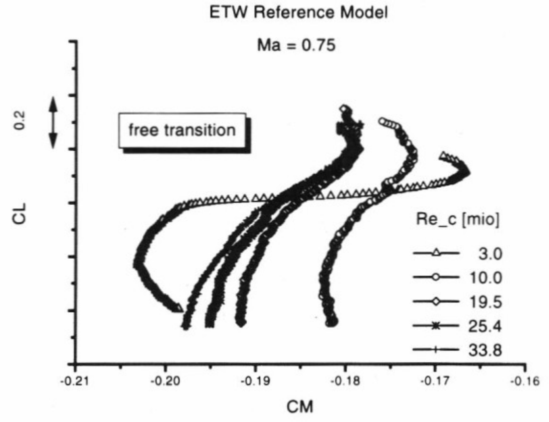

Fig. 13 Lift versus pitching moment for different Reynolds numbers

In figure 13 the lift versus pitching moment is presented for continuous sweeps performed at different Reynolds numbers and a Mach number of M = 0.75. The scatter of data during the polars is less than 4×10^{-4} in CM for the shown raw data and mainly based on the achieved operating point stability during a polar.

For Re_c = 3 millions, the existence of large laminar flow areas on the wings is reflected by an increase of negative pitching moment for constant CL. Increasing Reynolds number also causes a shift of the curves in the same direction.

Data Quality

The data quality obtained during model test campaigns reflecting the present status of ETW is summarized in Table 1.

The stability of the test conditions is achieved by the control system with the beneficial effect of a choked 2nd throat, fulfilling the tight specification which has been set up for ETW.

Typical model results during test campaigns

Mach stability		
	T > 200 K	± 0.0005
	T < 200 K	± 0.001
Pressure stability		
	Δ Pt / Pt	< 0.002
Temperature stability		
	T > 200 K	± 0.3 K
	T < 200 K	± 0.1 K
Flow angularity		
	α	= 0.02 deg
Flow curvature		
	tail off ΔCM	= 0.0003
Repeatability		
	short term	< 0.5 count
	long term	≈ 1 count

table 1

Testing the model in upright and inverted position, upwash and flow curvature are worked out by comparing the lift and pitching moment coefficients. The values stated above were found to be constant over the Mach and Reynolds number range. Analysed for a variety of military and civil aircraft configurations, no model related influence was detected.

In wind tunnel testing, the question always addressed is about the repeatability of obtained results. Generally we have to distinguish between three types of repeatability:

The polar to polar comparison, a regular check in ETW by repeating a polar after a set of sweeps at different Mach numbers before changing the operational pressure or temperature,

run to run comparisons considering two polars with at least one change of pressure or temperature level in between them,

campaign to campaign comparisons, the model can be either kept untouched and only detached from the sting - boss (e.g. moving the model from one model cart to the other) or completely disassembled between two entries.

Except the last one, all cases were analysed. In the range of -5 .5 < α < 1.5 deg the repeatability in CL is better than ± 0.002 and in CM < 0.0003.

The comparison of drag polars is presented in figure 14 for a Mach number of 0.75 and Re_c = 14.6 millions.

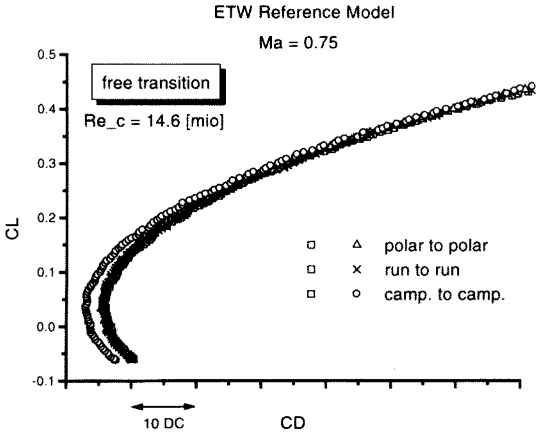

Fig. 14 Repeatability in drag

For short and medium term repeatability the achieved agreement is perfect. Considering the drag results obtained in two different test - campaigns, a constant shift of about 2.5 counts can be noticed. It is important to point out that all polars presented in figure 14 have been performed without any transition fixing on the model. Hence, even at this Reynolds number local laminar flow areas may exist. Before the first entry (indicated by circles) the model surface was polished to be suitable for testing under natural transition condition. Subsequent to the test runs the model was stored for about three months in the model preparation area in ambient environment.

Technique development

During the recent period of model testing experience has been gained in a number of techniques which are listed in table 2.

It is obvious that in some areas further development and/or refinement is required. Regarding the release of full transonic speed operating range in late 1995, only limited experience could be gained at very low temperatures. Nevertheless it was proved that all instrumentation in heated enclosures worked reliably under most severe environmental conditions. Hence, the availability of qualified tools for accurate high Reynolds number testing can be stated.

Measurement Techniques

Combined force, moment, and pressure measurements

Forces and moments using cold internal balances

Pressure plots using PSI units in heated housings

Various cryogenic filler materials

Transition fixing using
carborandum
ballotini
dots

Transition detection using acenaphthene in warm conditions

Transition detection using an IR - camera for $T \geq 200$ K

Table 2

Productivity

One of the most important criteria to be fulfilled by a commercially operated facility is its productivity. During the early model tests in ETW the overall productivity was limited by the need to develop techniques and to gain experience in parallel to the polars. Additional restrictions due to tunnel development and specific requirements to match conditions for data comparison do presently not allow to make final statements.

Early indications during this phase of technique development show that the productivity targets set for ETW can be achieved.

But the recently performed campaign to determine flow angularity and turbulence level in the test - section by operating the Rotating Rake no. II is suitable for some interesting considerations. As productivity assessment is mostly based on the number of productive polars being performed within a certain period, it is essential to define what a polar means in that context. In standard ETW terminology a polar is defined as a model sweep over a pitch range at constant tunnel operating conditions, recording force and moment and / or pressure data. During the campaign considered here, more work was done in a polar. To calibrate the five - hole probes, the rake was pitched from zero to + 0.5 deg, then to - 0.5 and subsequently back to zero degrees. This pitch sequence was repeated at zero, 90, 180 and 270 deg roll. After each pitch, the rake was rolled to the next circumferential position while data were recorded.

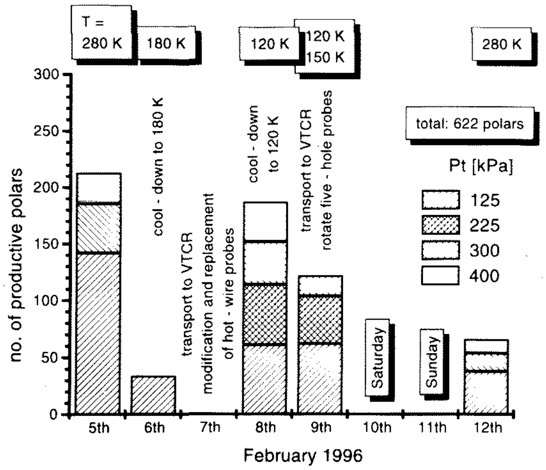

Fig. 15 Productivity statistics

A polar was closed by rolling the rake back to zero roll / pitch position (total time about 2 minutes) to proceed with the next set point in Mach number, pressure, or temperature.

Figure 16 presents an outline of performed activities and achievements. The total number of 622 productive polars taken at pressure levels between 125 and 400 kPa and Mach numbers ranged from 0.2 to 0.95 were interleaved with a tunnel cool - down to 120 K. Additionally two cold model cart transfers to a VTCR were required and successfully carried out at 150 K, to replace damaged hot - wire probes and to rotate five - hole probes for a reliable in situ calibration. As a consequence of these interruptions of the test program, we had to perform an additional short cool - down from 150 to 120 K, while the second time the temperature was modified in set point change mode. Starting a natural warm up on Friday night, it was accelerated by running the compressor for heat generation and completed on Monday morning to collect the final data over the rest of the day.

Data correction

All results of model tests being presented in this report are without any correction for buoyancy, wall- or sting-interferences. But the ETW standard data reduction procedure makes allowance for

sting deflection
model weight
upwash.

For the determination of absolute drag levels, sting and wall effects on the tested model have to be known. First steps were made to investigate the sting and tunnel generated buoyancy on the centreline. As the ETW "Short Axial Probe" accurately reflects the geometry of the "Short Sting", as already mentioned above, the obtained pressure distributions can be used to calculate the total buoyancy for the reference model in straight sting mounted configuration. Based on the centreline pressures presented in figure 9, the calculated buoyancy drag for the Reference Model at zero incidence is given in figure 17. For PMR 2, the point of model rotation commonly used for transport aircraft model testing,the bouyancy drag drops with increasing Mach number from 13 counts (M = 0.2) down to about 3 counts for M = 0.98. Comparitative calculations with a linearized potential flow method show acceptable agreement for M ≈ 0.8 and a contribution of tunnel (i.e. sting boss / sector) in the order of about one count.

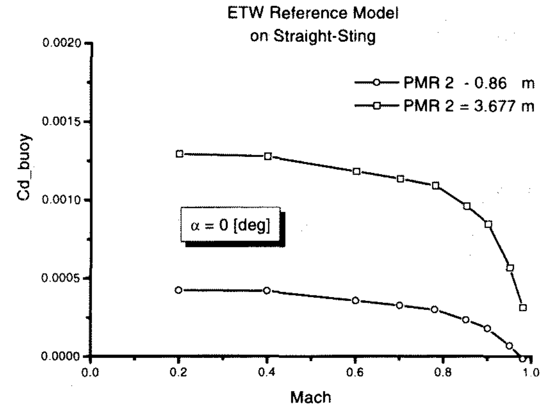

Fig. 16 Buoyancy drag for the ETW Reference Model

The dominating effect on the axial pressure gradient is generated by the first taper of the sting. This is documented by the 2nd curve in the above figure. Here an upstream model shift by 0.86 m is supposed (e.g. by inserting a parallel adapter to extend the cylindrical part of the sting). Hence, leaving the strong pressure gradient in the vicinity of the taper, the resulting buoyancy drag is remarkably reduced and even completely cancelled for very high Mach numbers.

First investigations have been made by one of the mother establishments for the assessment of wall interference. Preliminary results are very promising and point to neglectible levels for the Mach number range around M ≈ 0.8.

Summary

After the modification of the liquid nitrogen injection system the tunnel was declared as being operational over its designed subsonic / transonic operating range. The performed calibration campaigns covered Reynolds numbers from 3 to 52 millions (referring to M = 0.8) and confirmed that the specification is met on flow quality and homogeneity in the test - section.

Using the ETW Reference Model the capability to measure Reynolds number effects on the aerodynamic coefficients was documented. An excellent accuracy and repeatability of the obtained results can be stated.

The high quality of results is also confirmed by comparitative tests with other facilities on Airbus models at ambient conditions.

An extended operational experience and improved knowledge about cryogenic testing allow us to achieve a high productivity rate.

First estimates of sting and wall interferences show promising results and will be validated by ongoing analysis of recent campaigns as well as experimental investigations scheduled for the near future.

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