ETW

USER GUIDE

Revision A

Flight Reynolds Number Capability

Cost Effectiveness

High Data Quality

Client Confidentiality

Test Productivity

European Transonic Windtunnel

SUMMARY

This guide is to give prospective users of the European Transonic Windtunnel, an introduction to the facility, an insight into its capabilities, the procedures employed and the services offered. The intention being that it will enable the prospective user to assess the tunnel performance against his programme requirements.

Report Number:
ETW/D/95001/A,
Original Issue: Feb 1995
Revision A Jan 2004

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1 INTRODUCTION

The European Transonic Windtunnel GmbH (ETW) was founded on 28 April 1988 by four European countries: France, Germany, Great Britain and The Netherlands.

ETW GmbH is a company with limited liability according to German law and its seat is located close to the Cologne/Bonn airport in Cologne, Germany.

The objective of the Company was to construct, operate, maintain and further develop a high Reynolds number transonic wind tunnel facility.

After many years of joint preparatory investigations and preliminary design work, the final design of the wind tunnel plant and selection of major mechanical and civil contractors was accomplished in 1989. Construction work started early in 1990 and at the end of 1992, the facility was completed.

Since 1995, after careful commissioning and calibration, ETW has been in full operation and has, in numerous test campaigns, proved to meet the design specifications.

ETW provides high quality wind tunnel test data at actual cruising flight Mach and Reynolds numbers and is open to clients from all over the world.

1.2
Basic Aspects

The original motivation to build facilities for flight Reynolds number simulation of aircraft models was based on significant differences between wind tunnel tests and real flight, often leading to costly design changes after the first flights of a new aircraft. Nowadays, with the availability of advanced CFD methods, some Reynolds number effects are better understood but so called ‘indirect’ Reynolds number effects are still difficult to predict. Flight performance testing with buffet onset investigations and drag reduction on attached components, etc. are typical objectives focussed on high Reynolds number testing.

Striving for a capability to analyse such effects by experimental investigations on a wind tunnel model, obvious requirements are :

- a wide Reynolds number range, ideally up to flight conditions,
- the independent variation of tunnel parameters to separate between aerodynamic and model deformation effects,
- the extraordinary quality of steady and dynamic flow to generate conditions comparable to flight, based on a high level of tunnel set point stability and repeatability,
- the tools and techniques to measure and visualize aerodynamic effects close to the surface of the aircraft model,
- the instrumentation for measurement of specific test assembly characteristics, like wing deformation, sting interference, model dynamics.

The test objectives listed above influence the model design in the early stage of the project. Design inputs will be provided by ETW concerning the tunnel test envelope, the installed instrumentation with relevant interfaces and the possible use of different test techniques. A typical example is the maximum achievable dynamic pressure, which is not only the basis for all model stress computations, but also determines deformation dependent design details.

Detailed discussions between the client and ETW specialists are therefore essential during the early stages of a test project.

1.3
Organisation

The organisation and staffing of the company is designed to allow ETW to operate efficiently whilst providing clients with all necessary services in relation to wind tunnel testing.

The complement of ETW staff includes experienced test engineers and aerodynamicists, experts in the fields of design, data processing and test instrumentation, and skilled technicians for model rigging, wind tunnel operation and workshop tasks, together with the necessary safety, security and administrative functions.

The official language of ETW is English, however, communication is also possible in both French and German.

ETW GmbH holds a certificate according to EN ISO 9001:2000 issued on behalf of the accreditation bodies of the four participating nations by Lloyd’s Register Quality Assurance Ltd., following a thorough assessment and regular audits of the quality management system.

1.4
Purpose of the Guide

The purpose of this guide is to give prospective users of ETW an introduction to the facility, an insight into its capabilities, the procedures employed and the services offered. It is hoped that this will enable them to assess the tunnel performance against their programme requirements. If for any reason these requirements appear not to be met then ETW would be pleased to discuss them further.

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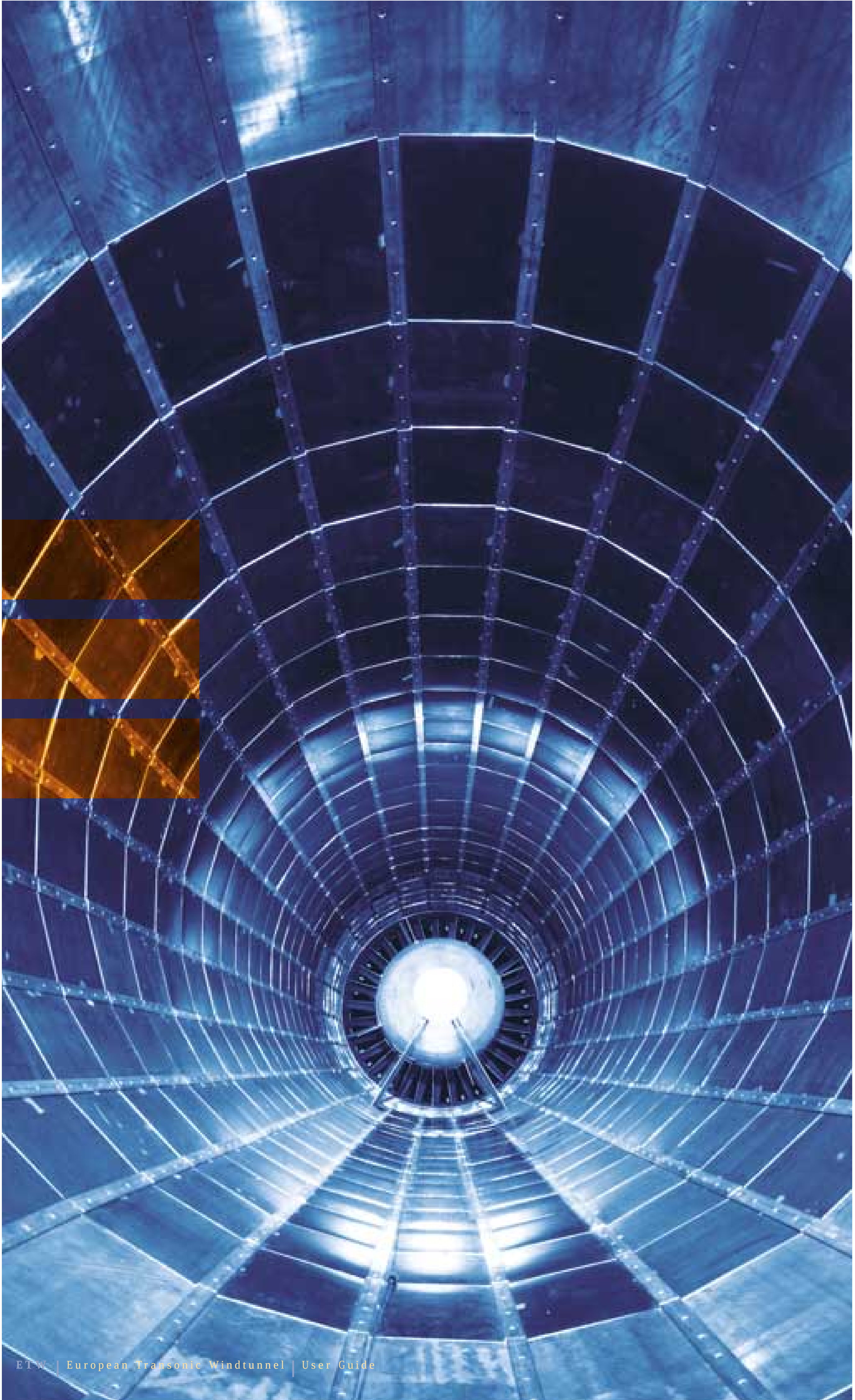
DESCRIPTION OF THE FACILITY



2.1 ETW Characteristics

The ETW facility is a high Reynolds number transonic wind tunnel using nitrogen as the test gas. High Reynolds numbers are achieved under the combined effects of very low temperatures and moderately high pressures.

The Mach number ranges from 0.13, for low speed testing, through the range of high subsonic speeds important for the cruising flight of modern transport aircraft, up to 1.3, for supersonic aircraft or space vehicle tests in low supersonic conditions.

ETW Specification	
Test section size	2.0m x 2.4m
Mach number range	0.13 - 1.3
Pressure range	115 to 450 kPa
Temperature range	110K to 313K
Max. Reynolds number/c with c = reference length	$230 \times 10^6 \times 1/m$

The test section size and the pressure and temperature ranges represent the best combination of parameters to meet the requirement from the aerospace industry to achieve, with full span models (span about 1.5m), a Reynolds number of 50 million at cruise conditions for large transport aircraft, and up to 90 million with vertically mounted half models (semi-span about 1.3m). The operating range expressed as Reynolds number vs. Mach number is presented in **figure 1**.

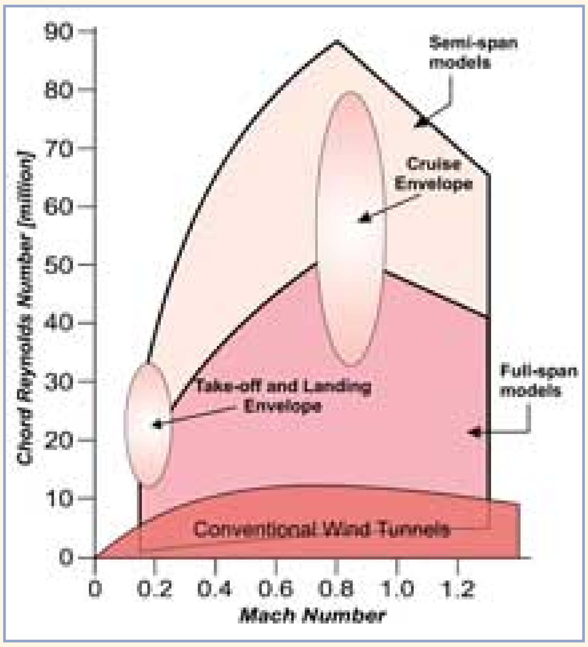


Figure 1: Performance Envelope of ETW

ETW has advantages over conventional wind tunnels other than the increase in Reynolds number, in that the Mach number, Reynolds number and dynamic pressure can all be varied independently. This capability allows the following test trajectories to be accomplished:

Reynolds number effects can be obtained without varying the aeroelastic distortion of the model. This is achieved by changing only the temperature, whilst holding Mach number and pressure (and therefore dynamic pressure) constant. An example of the trajectory of such a test is shown on the operational envelope in **figure 2**. This feature enables Reynolds number extrapolation for a model where full scale Reynolds numbers cannot be attained.

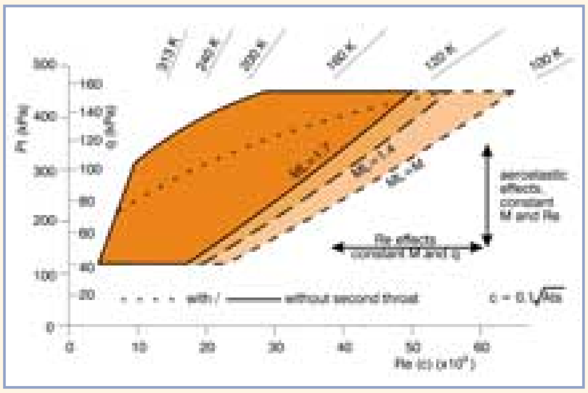


Figure 2: Example for Test Trajectories for Reynolds Number and Aeroelastic Effects, Holding Mach Number Constant (M=0.9)

Pure **Mach number effects** can be obtained by varying the stagnation pressure and temperature in order to hold dynamic pressure and Reynolds number constant when the Mach number is changed.

The **effects of aeroelastic deformation** of models can be studied by varying the dynamic pressure, whilst holding the Mach number and Reynolds number constant, as indicated by the trajectory line indicated in the envelope of figure 2.

Testing in ETW can also be carried out at ambient temperature as in conventional wind tunnels whilst the mentioned special features of ETW remain valid. This has the extra advantage of being able to provide the continuity of data from cryogenic to ambient conditions (high to low Reynolds numbers), and to compare results against tests in other conventional tunnels with the same model.

In addition, ETW offers absolutely stable and accurately repeatable test conditions over the full temperature range from cryogenic to ambient regardless of the time between tests.

2.2
Aerodynamic Circuit

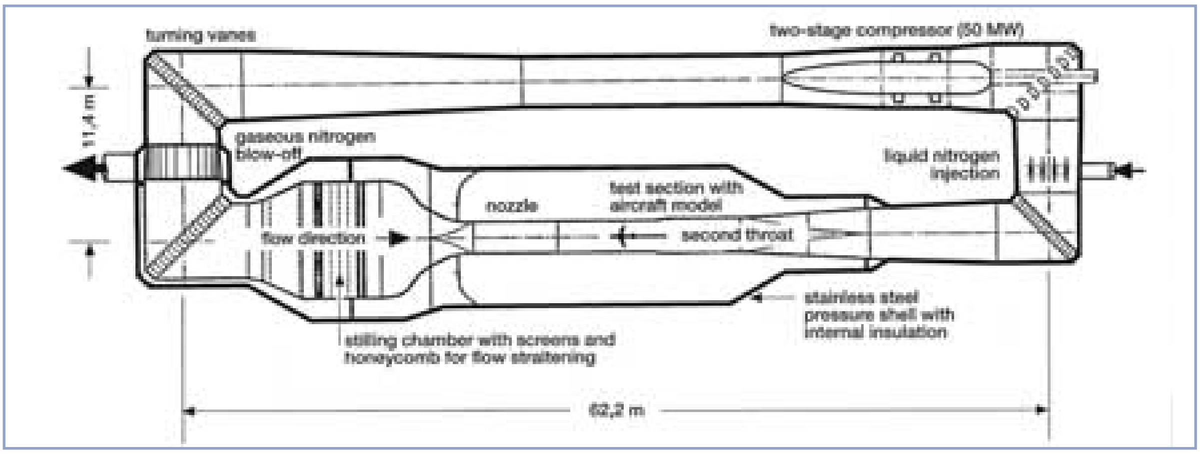


Figure 3: Aerodynamic Circuit

ETW has a closed aerodynamic circuit (**figure 3**) contained inside an internally insulated pressure shell. This pressure shell and all internal structures are made of stainless steel which does not embrittle in the cold nitrogen environment. The compressor with a maximum drive power of 50 MW circulates the nitrogen gas around the circuit. To achieve and maintain the desired low temperature of the test gas, liquid nitrogen is continuously injected into the tunnel, upstream of the compressor where it immediately vaporizes, forming the cold wind tunnel gas. In order to maintain the desired pressure, a corresponding mass flow of gaseous nitrogen is exhausted upstream of the stilling chamber.

The overall layout of the circuit and especially the stilling chamber area, nozzle and test section are consistent with the high flow quality required for high Reynolds number testing.

The test section is equipped with the capability of having all four walls individually closed or slotted (**figure 4**).

Figure 4: Aircraft Model in the ETW Test Section

Test section details:
Dimensions (HxWxL): 2.00m x 2.40 m x 9.00m (incl. re-entry).

Wall Configuration:
Top and bottom walls
- 6 slots each, with 6.25% porosity
- wall angle remotely adjustable

Side walls
- 4 slots each, with 7.4% porosity

Re-entry area
- provided by movable finger flaps (one per slot)

Optical access provided in all walls

For full model testing, the standard test section configuration has slotted top and bottom walls with an overall effective porosity of 3.4%. For high speed half model testing, the standard test section configuration has slotted side walls with an overall porosity of 4.6%.

Downstream of the test section is the adjustable second throat, which serves to minimize flow disturbance propagating upstream and to provide Mach number control during tunnel operations. The second throat is normally used for $0.65 < M < 1.0$ operation.

2.3
Flow Quality

ETW has a flow quality at least as good as the quality obtained in the best conventional transonic wind tunnels and, in some ways better, being consistent with high Reynolds number testing.

The flow quality requirements are applicable in the model test volume, i.e. over a test section domain centred on the sting mounted model centre of rotation, with a length of 2.4 m and a cross section extending to within 2 boundary layer thicknesses from the walls.

The Mach number spatial uniformity shows a maximum deviation of ± 0.001 in subsonic conditions and ± 0.008 in supersonic conditions within the test volume. These deviations are applicable for an empty test section and are to be seen as 3σ values i.e. virtually peak to peak values.

Thermal distortions after a temperature change are within tolerance 2.5 minutes after a 40 K change at 3 K/sec, or 5 minutes after inserting a model cart in the tunnel, or 30 minutes after a full range tunnel cooldown at 80 K/hour.

The control system is designed to maintain the time variations of the Mach number during a polar below ±0.001 over the full M range. It has a set point change capability (resolution) of 0.001 in Mach number. It is also designed to prevent the relative time variations of the total pressure in the tunnel from exceeding 0.2%, i.e. $\Delta Pt/Pt \leq 0.002$, during a polar.

The temperature set point during a polar is kept to within ± 0.5 K. This corresponds to the specified temperature uniformity within the test volume.

The above capabilities in pressure, temperature and Mach number stability result in a Reynolds number stability of better than $\Delta Re \leq 0.005 \times 10^6$.

As far as the flow direction in the test section is concerned, ETW achieves a deviation of less than 0.1 degree, repeatable and measurable to within ± 0.01 degree.

High Reynolds number simulation requires the turbulence intensity in the test section not exceeding 0.05%. This ambitious goal is achieved by using 4 screens and a honeycomb of large depth/cell diameter ratio in the stilling chamber, and a nozzle contraction with a 12 to 1 ratio.

2.4
Model Handling and Productivity

In order to meet the productivity goals, ETW has developed a removable model cart system for operation in the cold environment. Along with the model and its supporting structure, a model cart consists of the test section top wall, the pressure door (hatch cover) of the tunnel and the instrumentation cabin (**figure 5**). This entire assembly of approximately 200 tonnes is removed in one unit by the remotely controlled model cart transporter. Two model cart assemblies are provided for full models. By exchanging the slotted test section top wall with a solid half model top wall, including a turntable and an external five-component balance, one of these model carts can be modified to accept vertically mounted half models (**figure 6**).

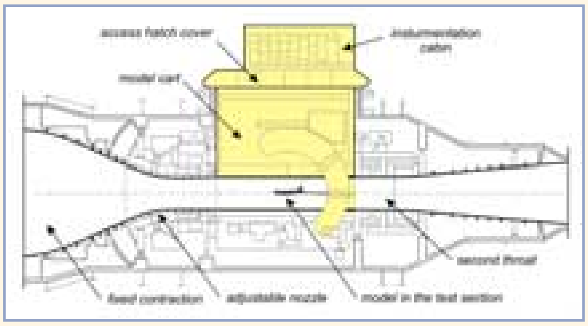


Figure 5: Test Section and Plenum

Figure 6: A Half Model in the ETW Test Section

A key element of ETW is the efficiency at which the clients can be accommodated in the facility, their models prepared and the speed and accuracy at which the data can be acquired. The achievable productivity can be expressed as 3000 polars per year utilizing the present two model carts. Various activities, such as model preparation, cart-rigging, model testing, model configuration change, model conditioning and check-out can take place in dedicated rooms in parallel. The general layout of the building is consistent with the possibility of interleaved operations in order to achieve both efficiency and confidentiality.

Once lifted from a Cart Rigging Bay (CRB) the transporter can move and lower the model cart assembly into any of the other rooms along the transfer hall including the test section of the tunnel (**figure 7**).

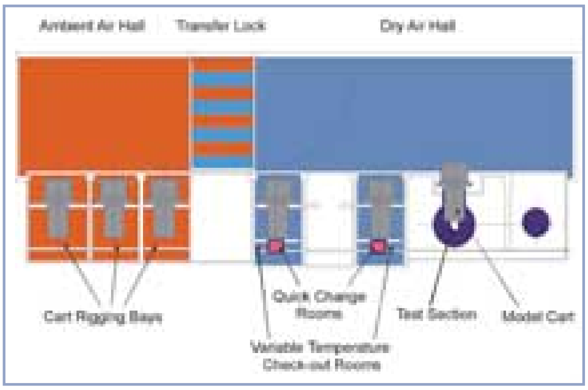


Figure 7: Section through Transfer Hall

This transfer hall consists of two sections, one above the CRBs at ambient air conditions and the other above the Variable Temperature Check-out Rooms (VTCRs) and the test section, this part of the hall containing ambient temperature dry air to prevent frost and ice build-up when the model and cart assemblies are cold.

The two sections of the transfer hall are separated by a transfer lock, which enables the purging of all humid air from the model and cart assembly, prior to moving into the dry air areas of the facility.

The VTCRs are also fed with dry air which can be varied in temperature from 313 K down to 110 K. The VTCRs are divided into two main areas by means of large horizontal sliding doors: the Temperature Conditioning Room (TCR) for the model cart above these doors and the Quick Change Room (QCR) below the doors (**figure 8**). The QCR receives the model and the front end of the model support system and provides the possibility of conditioning just the model for quick configuration changes between two runs, without changing the temperature of the complete cart.

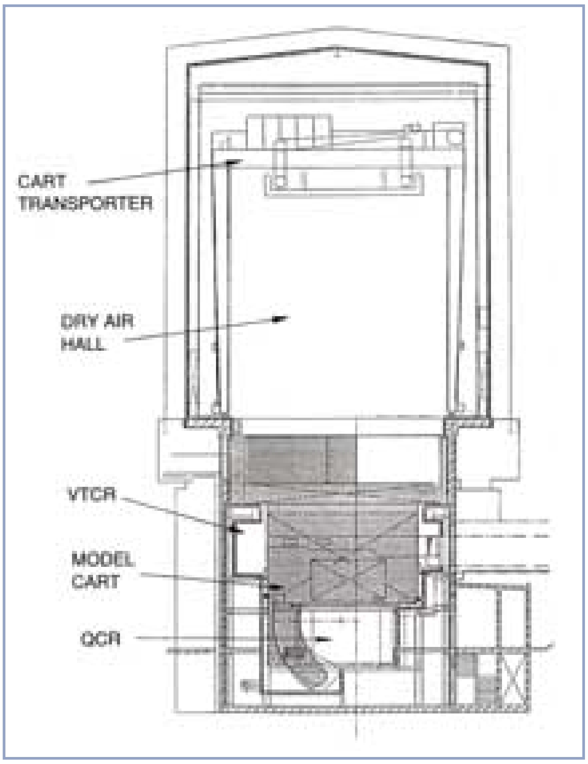


Figure 8: Section through VTCR

The activities that can be undertaken in the QCRs are:

- model configuration changes
- model instrumentation checking in cold conditions
- specific calibrations requiring the model to be immersed in the cold, including loads application
- investigation of the effect of transient conditions on test data
- temperature conditioning of model and cart, ready for testing.

2.5 Wind Tunnel and Model Handling Control Systems

Two separate control systems enable the operators to manage the different activities of the whole plant. The first unit, the Windtunnel Main Control (WMC), synchronizes the activities of the sub-systems (compressor/drive, nitrogen injection system, blow-off system, second throat, supersonic nozzle) in order to perform the test runs (start up, set point changes, set point maintaining during polars, shutdowns) with a

DESCRIPTION OF THE FACILITY

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high level of safety and economy. These activities are usually controlled in automatic mode with the possibility of manual interventions from the main tunnel control room (**figure 9**). The second unit, the Model Handling Control (MHC), synchronizes the activities of other sub-systems (cart transporter, remotely operated doors, purging system, temperature conditioning system) and generally provides the capability to perform auxiliary tasks.

Figure 9: Main Tunnel Control Room

2.6 Monitoring System

The monitoring system allows the operators to observe all the components of the plant and to analyse the behaviour of the main parameters. It provides for real time observation, can send alarms if failures are detected and gives details of the reasons for failure. It is able to relay necessary information to the control system in order to increase the safety level. The Control and Monitoring Systems (CMOS) are extremely reliable and user friendly. Through the use of computer screen images and a screen-pointing device, operators can easily access nearly every control or monitoring parameter throughout the facility.

2.7 Data Systems and Instrumentation

The ETW data systems ensure both the strictest confidentiality of test results and the flexibility and "comfort" that clients generally require from industrial wind tunnels.

Model data acquisition is performed close to the model in the instrumentation cabin which remains with the model cart. The acquisition system comprises:

- a large number of transducers for forces, pressures, temperatures, attitudes, positions, etc. both in the model and inside and around the wind tunnel
- the related sensor conditioning, amplification and analogue-to-digital conversion in the data acquisition systems
- a dedicated data acquisition computer.

Signal conditioning and analogue-to-digital conversion (ADC) feature great flexibility and high resolution for dealing with different types of sensors and signals.

3 TEST CAMPAIGN ORGANIZATION AND MANAGEMENT

3.1

Initial Contacts, Testing Contract

Enquiries by the prospective client requesting further information regarding a possible test entry should be made to the ETW Managing Director. After preliminary discussions defining the test requirement and schedule, an ETW test engineer will be nominated to be the point of contact throughout the test, ending with the final test report. The test engineer will co-ordinate all personnel and services to ensure a prompt response from ETW to all queries related to the tests. This test engineer will work with the client to optimise the test sequence taking into account the facility characteristics to provide efficiency in terms of cost and duration.

Principally, a test campaign will be covered by a contract signed by ETW and the client. A contract basically consists of a Contract Agreement and several Annexes:

- the Contract Agreement signed by both parties defines the parties, the ETW contract number, the scope of work, the remuneration and payment terms, the time-schedule and all annexes forming an integral part of the Contract.
- the different Annexes detail:
  - the General Conditions of Contract applicable to all contracts with ETW for test campaigns,
  - the Special Conditions of Contract applicable specifically to this contract,
  - the test programme as agreed between ETW and the client,
  - the test time-schedule.

Any change to the test programme having an impact on price or time-schedule is subject to the Contract Change Procedure in accordance with the Contract Conditions.

If the relation between the client and ETW is already well established, test campaigns can also be governed by a purchase order of the client, based on an ETW quotation for the respective testing programme.

3.2

Security and Client Confidentiality

An important aspect to every client is the security of his test; how safe, from prying eyes, is the model, the test programme, the test results, etc.

The entire staff assigned by ETW to a client test are ETW employees. All ETW employees have signed confidentiality agreements and are regularly made aware of their responsibilities.

Throughout the design of the buildings, the tunnel, the control system, the data acquisition and data reduction systems, ETW has taken security concerns into account. Below is a brief overview addressing each of these areas.

3.2.1

Buildings

Figure 10 shows the general layout of the user areas of ETW. ETW can provide three clients with complete privacy at any one time for all aspects of wind tunnel testing and the associated data processing.

Each user is allocated a set of three rooms: a Model Preparation Room, a Cart Rigging Bay (CRB) and a Data Analysis Room. In these rooms the client can undertake the model preparation, rigging, ambient temperature checkout, cart installation and data analysis in complete confidentiality. These rooms are for his use only, for the full duration of the test. Access to these rooms, and others in the facility, is controlled in agreement with the client, by the use of magnetic cards. New access codes are given to each test and can be changed on a time basis, if required.

Access to the variable temperature areas of the facility is controlled directly by ETW staff, for safety reasons. This means that the client, needing to work in these areas, will be accompanied by at least one member of staff knowledgeable on the systems and procedures for the cold environment.

Each of the clients' analysis rooms has a door to the main tunnel control room, however, only the client whose model is in the tunnel has access to the control room. The doors to the other clients' rooms are locked and controlled by ETW.

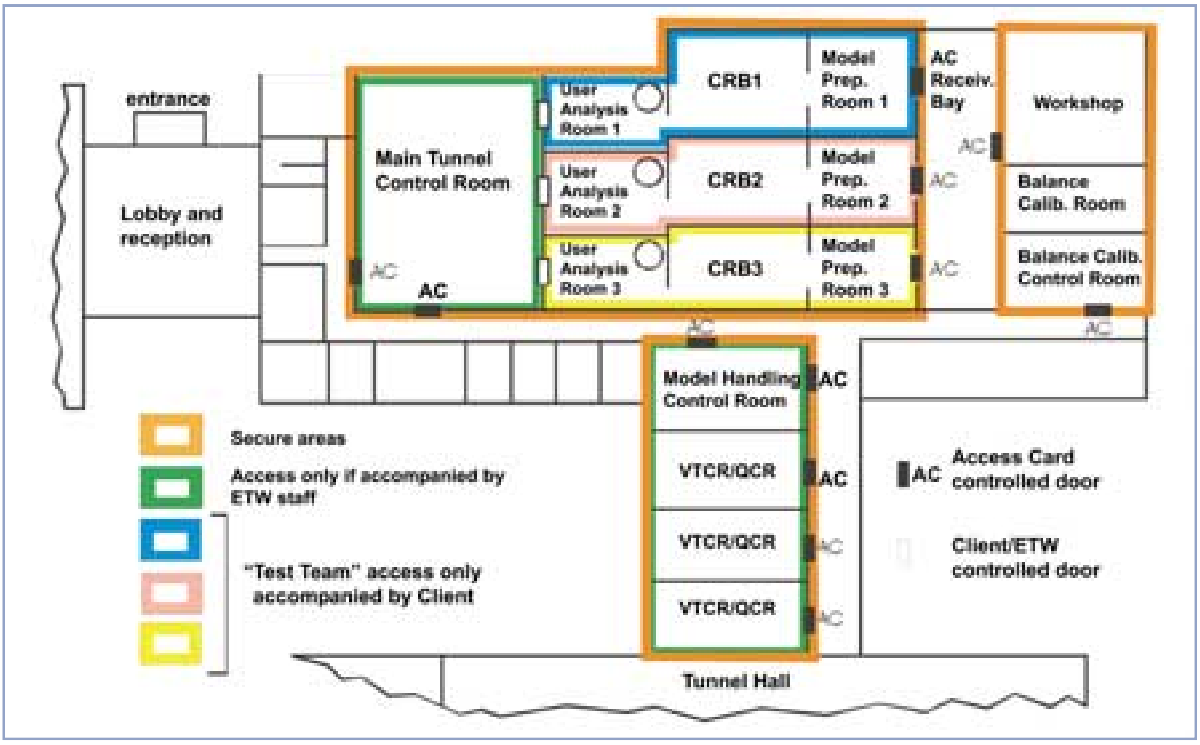

Figure 10: Part of Building Floor Plan

3.2.2 Computer and Data Systems

ETW are dedicated to protect all client data from disclosure and misuse and will ensure this protection through personnel, physical, logical and procedural measures.

On the technical side, the prime elements of security are physical and logical separation of data, and access control on a strict 'need-to-know' basis.

ETW has three dedicated, independent data processing computer systems, one for each User Room.

Client test data are stored on separate and removable disks or tapes in each User Room, which are physically removed from the system and kept in safe custody except for authorized applications. For an ongoing test, data acquisition, data processing and data display are performed on a separate dedicated network segment in a restricted area. Where network or other data lines leave this restricted area, logical filters and network bridges ensure that no access to the system is possible from outside, and no client data are transmitted on such lines. Where patching of network interconnections is possible, the patching is as transparent as possible and is subject to inspection by client's and security staff. Connections are mainly by fibre optic cables to avoid interception through radiation.

The Virtual Memory System (VMS) operating systems security is used to authenticate users and to restrict access to all computers. For critical cases, complete physical separation and electromagnetic shielding of the data processing system is possible.

All ETW personnel are kept aware of security requirements and are contractually obligated to security and confidentiality.

3.3 Quality Assurance

ETW has appointed a Safety/Security Officer and a Quality Engineer, responsible directly to the Managing Director, for all aspects related to quality assurance and control of the facility, equipment, personnel and results. ETW is certificated according to the international quality standard EN ISO 9001:2000.

As part of a regular product assurance programme, all components associated with the generation of test data, the actual tunnel, its instrumentation and data systems etc., are periodically checked by the ETW team. In addition, repeatability tests with calibration probes and reference models are regularly carried out to confirm that the high degree of quality is maintained throughout the years.

3.4 Provision of Services

At an early stage in the discussions on the test programme, the details of the services to be provided and the level of ETW staff participation need to be addressed. A client may, for reasons of model complexity or confidentiality, select to undertake the model preparation, rigging and data analysis unaided by ETW staff. In this scenario, ETW would enter discussions with the client to determine the model and data quality control and assurance procedures. This would cover aspects related to model integrity, strength, inspection procedures and data accuracy and repeatability covering model and tunnel performance.

Whilst many aspects of the services provided by ETW do not differ from the common practice in present large conventional wind tunnels, the key elements related to high Reynolds number testing and productivity are unique to ETW. Included in these services are the following:

- Provision of the Model Design Handbook which outlines the criteria for the design, construction, analysis, quality assurance of test assemblies and components for testing in ETW.
- Advice on model design, instrumentation and test techniques, many of which are specific to ETW.
- Evaluation of client test programmes to optimize the test objectives with cost effectiveness of operation, and to determine the scope of data processing.
- Estimate of test duration and cost of client programmes.
- Testing of the client's model and the supply of test results.

ETW can also provide, if required, services to undertake or assist in:

- model preparation,
- model rigging and configuration changes,
- software development,
- data analysis,
- instrumentation calibration.

ETW also has available a small machine shop where running repairs or modifications to equipment can be made either by ETW staff or by qualified client personnel.

The following test equipment is offered for use at ETW (see detailed description in section 6):

- model supports,
- internal strain gauge balances (full models),
- half model balance,
- model instrumentation,
- balance calibration facilities,
- engine simulation (future).

3.5 Survey of Testing Operations

Many client related activities are taking place in ETW simultaneously. Some of them during the pre- and post-test phases involve test engineers, design office staff, instrumentation specialists, and software specialists for relatively long periods. Several other activities require intensive mechanical and experimental work on models at different stages of the test campaign. Other activities are of a short duration on an ad-hoc basis. For one typical test campaign the schedule could be:

- 3 to 12 months for test preparation, generally undertaken out of ETW premises. This may include model fabrication.
- 5 to 15 days for model/equipment integration, normally undertaken in an ETW Model Preparation Room.
- 1 or 2 days in a Cart Rigging Bay (CRB) for model mounting, calibration and checking on a cart.
- X days for the test, dependent on the test programme, incl. configuration changes in a VTCR.
- 1 day in a CRB for post-check and removal from cart.
- 1 or 2 days in the Model Preparation Room for disassembly and packing.
- 6 weeks to issue the test report.

These durations are only indicative and reflect the possibility of large variations according to the novelty and complexity of the test.

4 TESTING IN ETW

4.1

Test Objectives

Flight Reynolds Number Testing

The test objectives selected by the client define the type of model to be used in ETW. Full span models will be used on various sting supports, whilst half models are attached to the test section top wall of a model cart. The limiting parameter for the size of transport aircraft models is typically the span criteria, i.e. model span ≤ 65% of test section width (span ≤ 0.65 x 2.4 m = 1.56 m). For fighter and space vehicles the tunnel blockage criteria is often the decisive parameter, i.e. model cross section ≤ 0.5% of tunnel cross section. Transonic half models typically will be restricted in half span to 65% of tunnel height (0.65 x 2.0 m = 1.30 m). Low speed, high lift models might increase the span criteria to 75%. ETW will provide all inputs necessary to establish a well selected and optimized type of model. With full-span model testing, Reynolds numbers, based on the mean aerodynamic wing chord, of up to $53x10^6$ can be achieved, and $80x10^6$ with semi-span models.

The details on model sizing criteria are provided in the ETW Model Design Handbook (**ETW/D/95004 Revision A**).

Pure Reynolds Number Effects

By establishing the test programme, the maximum requested Reynolds number is the most important parameter. However, by determining a Reynolds number range the temperature and pressure levels have to be carefully selected and the overall strategy to control model deformation effects has to be clarified. ETW provides the ability to separate pure Reynolds number effects from model deformation effects by independent control of velocity, temperature and pressure. A typical test programme normally includes several levels of constant dynamic pressure q, as indicated in **figure 11**, for analysing pure Reynolds number effects. Due to a slight variation in the model's elasticity modulus, E, with temperature, ETW has adopted the method of using a constant value of q/E.

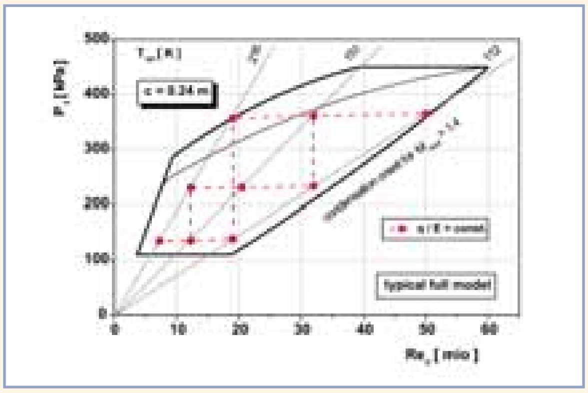

Figure 11: Operating Envelope for q/E testing

Model Deformation Effects

Repeating polars at constant Reynolds number at different dynamic pressure levels provides the opportunity to investigate pure model deformation effects.

Both Reynolds number and model deformation effects, as shown in **figures 12 and 13**, also affect the measured forces and moments. The pitching moment characteristics show the most dramatic variations, with both Reynolds number and aeroelastic effects clearly visible.

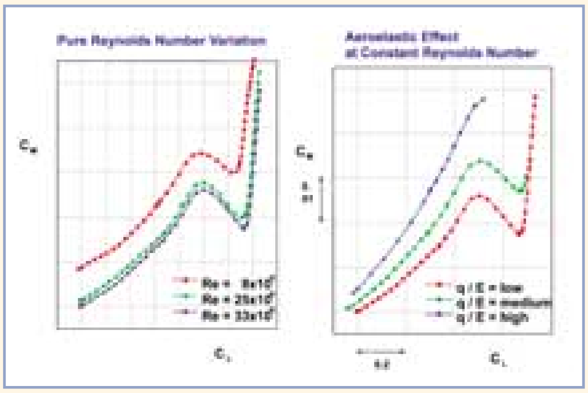

Figure 12: Pure Reynolds Number and Pure Model Deformation Effects on Pitching Moment

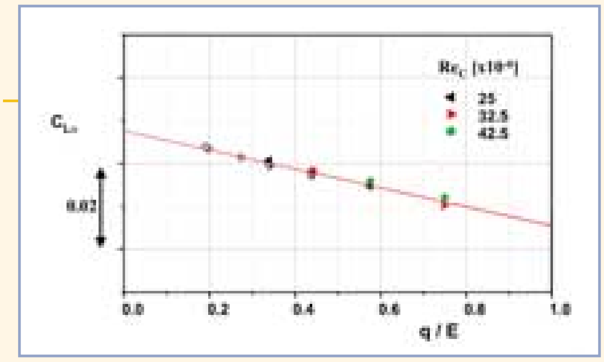

Figure 13: Aeroelastic Effects on Lift Curve Slope

The aeroelastic effects are also clearly evident in the lift curve slope characteristics whilst the associated Reynolds number effects are seen to be much smaller in comparison. From this review it is clear that extreme caution needs to be exercised when attempting to obtain true scale effects from wind tunnel test data. The ability to independently vary Reynolds number and dynamic pressure provides ETW's users with a distinct advantage in understanding scale effects. However, it is only by combining these capabilities with a well designed model and an appropriate test programme that real gains in understanding can be achieved. Although the issue of quantifying the actual model deformation at a particular test condition remains a difficult area, ETW offers three methods of determining the model deformation as outlined in Section 4.3.

Repeatability

A small number of repeat conditions are normally built into each test programme to confirm data quality. A typical example of the short-term repeatability is provided in **figure 14**, which includes two continuous traverse polars together with a pitch and pause polar. In general, the repeatability in drag is around 1 drag count irrespective of the traverse type and test temperature. Equally important is the level of repeatability of the measurement of pressures. From figure 14 it can also be seen that the agreement between the pitch & pause and continuous traverses is maintained throughout the entire incidence range, primarily due to the selection of a reduced traverse rate at incidences above buffet onset.

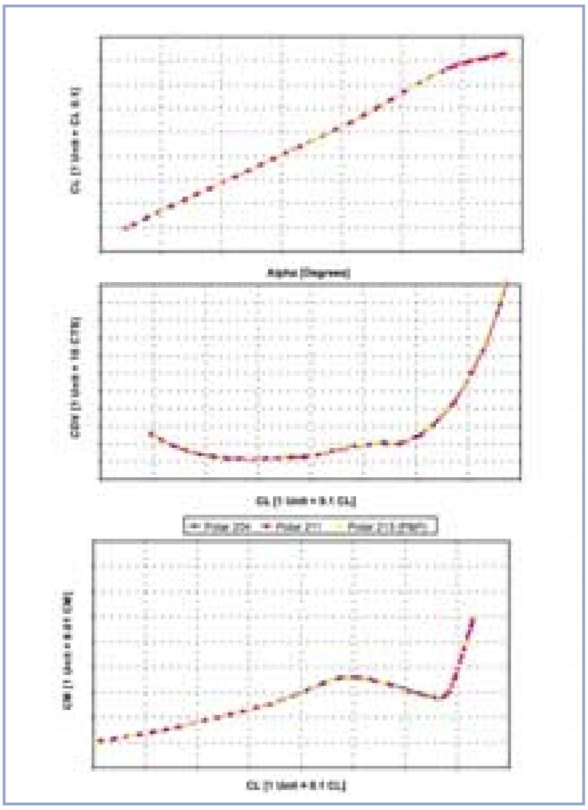

Figure 14: Repeatability of Test Data

In addition, an absolutely perfect long-term repeatability of test conditions is ensured regardless of the time between tests.

4.2 Measurement Capabilities

A brief overview of the standard techniques that can be employed at ETW is given below, however, this list should not be considered as comprehensive. For other types of tests or measurement techniques, further information will be provided by ETW in response to specific requests. Testing can be conducted either in the "pitch/pause" mode or the "continuous traverse" mode. The continuous traverse rate depends on the amount of measurements and the test objective. Typical values of up to 0.25°/s are used. In buffet onset region, the rate is reduced to 0.15°/s or even lower.

This section summarizes the general properties of various instrumentations used with models at ETW. Technical descriptions and lists of available components, together with interface information are given in Section 6.

Model Incidence

Model incidence is a fundamental measurement quantity normally measured at ETW with high precision Sundstrand inclinometers installed within a thermally controlled package. A resolution of 0.001° is achieved with the standard equipment and the estimated absolute accuracy for incidence measurement is around ± 0.005°. Special care is given to the installation of the model inclinometer box in order to minimize any thermal stresses and deformations being introduced into the model fuselage. Any deformation would create errors of the model incidence.

Forces and Moments

Model forces and moments are generally measured with a strain gauge balance. Full-span models in ETW are normally mounted directly on to the balance, which is internal to the model. The balance in this case measures six components: normal force, side force, axial force, pitching moment, yawing moment and rolling moment.

Semi-span or half models are mounted on a five component balance which is external to the model and is situated in the top wall of the test section.

The resolution of axial force, normal force and pitching moment is in the order of 0.01% of the full range capacity. The accuracy achieved is specified as 0.1% for the standard balances. In the testing sequence, attention is paid to ensure that thermal gradients inside the balance structure are minimized. ETW has adopted the method of running the normal sequence of Mach number test runs with constant recovery temperature to keep the balance structure absolutely stable.

Pressures

ETW has a number of PSI pressure scanners of various ranges (see Section 6.2) for incorporation into client models. These can be used for base pressure measurements, where only a small number of pressures are to be recorded, to full pressure plotting models where up to several hundred pressures can be taken. It is standard procedure in ETW to test in combined mode, i.e. force/moment and pressure measurements are acquired simultaneously.

The PSI units are maintained at a constant temperature. This results in an achievable systems accuracy for the pressure measurements of better than ± 50 Pa for the maximum range scanners of 30 psi (207 kPa), which corresponds to 0.02% accuracy of full range.

Temperatures

A number of balance temperatures are measured as a standard procedure in ETW to monitor thermal gradients. A similar measurement technique can be used to monitor temperatures in the model assembly if required. Normally the temperature is measured with Pt100 for general information and global stress observation. Any high accuracy measurements require specially calibrated Pt100s, which can be provided on request.

Dynamic Data

A High-Speed Data Acquisition System (HSDAS) is available compatible with the acquisition of signals from fast response instruments, such as Kulites. Additional details are provided in Section 6.2.

Anti-Vibration System (AVS)

In many wind tunnels, the testing of full span models suffers from vibrations of the test object, which can be excited by different mechanisms. Although these phenomena are known from conventional wind tunnels, cryogenic tunnels seem to be particularly prone to model dynamics due to a very low structural damping, and the low viscous damping at high Reynolds numbers in connection with high dynamic pressures at these conditions.

At ETW it has been shown by a modal analysis of the support structure and further measurements on the model suspension system that the vibratory system is essentially represented by a spring/mass system consisting of the sting/internal balance/model arrangement.

To minimize the effects of model dynamics, an active anti-vibration interface for full span model testing, located between sting and balance has been developed by ETW in co-operation with the German company ERAS GmbH. The active interface operates on the basis of counteracting vibrations at the eigenfrequencies of the model/balance assembly by exploiting the resonance properties of this system. Examples of the effectiveness of this interface are shown in **figure 15**.

After having gained experience from several test campaigns, a stronger actuator, located in the sting and operated jointly with the active interface, has been developed. This Anti- Vibration System (AVS) enables single sting supported models to be tested into the buffet region.

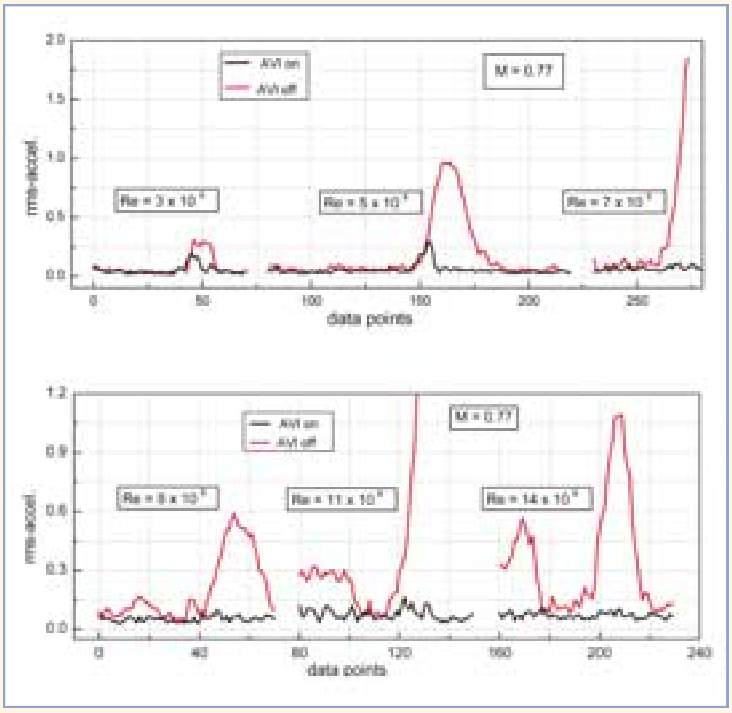

Figure 15: Effectiveness of the Anti-Vibration Interface

4.3

Complementary Testing Techniques

Transition detection

In addition to obtaining forces, moments, and pressures data, ETW provides different techniques for surface flow visualization. ETW operates two infrared camera systems, one with thermally controlled standard camera units for ambient temperature to 220 K and one for cryogenic conditions, covering 220 K to 110 K. The model requires a coating of 0.1 mm thikkness to be applied to the surfaces with the exception of the wing leading edges (first 3% of wing chord) and the pressure plotting rows. A photograph of the leading edge region is shown in **figure 16**.

Figure 16: Wing Surface Coating for the Acquisition of Infrared Images

In the region of the leading edges and at each of the pressure plotting stations, the target is to achieve a smooth transition between the coating and the metallic surface and to keep the overall surface roughness to less than Ra = 0.2mm.

For the specific task of boundary layer transition detection, images are taken just prior to, and during a rapid temperature step in the flow. Since the heat transfer rates are different for laminar and turbulent boundary layers, the temperatures seen by the IR camera system in the transient temperature range differ in the laminar and turbulent flow regions of the wing. Using the first images (before any temperature change) as a reference, the two areas can be clearly distinguished. A temperature step of about 10 K is required to achieve images with sufficient contrast; the ETW flow control can impose this step in a matter of seconds – well before the temperature gradient in the wing structure can equalize.

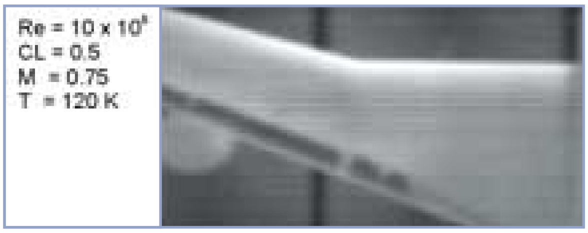

Figure 17: Infrared Image of a Typical Transport Aircraft Wing

An example of a processed image taken of the ETW Reference Model at 120K is provided in **figure 17**. Images taken over the complete Reynolds number range show the development of the boundary layer over a wide range of test conditions. At the highest Reynolds numbers, the images prove that transition from laminar to turbulent is either at or very close to the wing leading edge. At the intermediate Reynolds number shown in figure 17, areas of laminar flow are still clearly visible in the picture taken by the cryogenic camera system. This confirms both the functioning of the test technique and also the flow quality at ETW.

A side aspect of IR testing is that the applied paint can influence the aerodynamic data. The experience for transport aircraft models so far is that drag is typically increased by 2 drag counts, but lift characteristics are not affected.

In preparation for the use of Pressure Sensitive Paint (PSP), ETW is already able to apply Temperature Sensitive Paint (TSP) as an alternative to infrared thermography. Validation tests were carried out on the ETW reference model using a new type of TSP, which is particularly sensitive at cryogenic temperatures. The nontoxic paint is applied to the model wing surfaces in exactly the same way as other coatings that are used e.g. for visual or infrared imaging. It is then polished to a high quality surface finish. For image acquisition, the paint is stimulated by flashes of high power ultraviolet light. This energy, in turn, causes the TSP to emit red light with a temperature dependent intensity. A calibration is performed beforehand to quantify the relationship between intensity and temperature. The paint used in ETW exposes a linear sensitivity over the

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temperature range of 110 K to 170 K. A measurement grade CCD camera is utilized to acquire the raw data images, a typical exposure time being 1 second. Some post processing of the images is subsequently performed to remove background light by means of subtracting reference images. At the end of this process, the temperature distribution over the entire illuminated and acquired model surface can be quantified (**figure 18**).

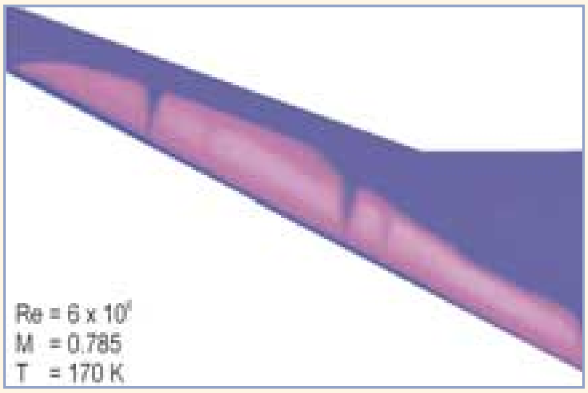


Figure 18: Visualization of Boundary Layer Details by Temperature Sensitive Paint

Flow visualization

To monitor and to document specific flow behaviour, a matrix of minitufts suitable for the cryogenic environment can be attached to the model surface and used throughout the complete test envelope. For low speed testing, for example, each tuft is individually attached with a thin Kapton tape to provide sufficient stability at highly unsteady flow conditions. **Figure 19** compares images taken at two different Reynolds numbers, at identical Mach number and angle of incidence of the model.

Figure 19: Flow Details Indicated by Minitufts

Far field flow observation with Laser techniques is in development. For example, a wake flow development can be measured with this technique. Seeding of the flow is achieved with water vapour at such a low level that the model is not affected in any case.

Model Deformation Measurement

ETW is currently offering its clients three independent methods to determine the wing deflection of a wind tunnel model (**see figure 20**).

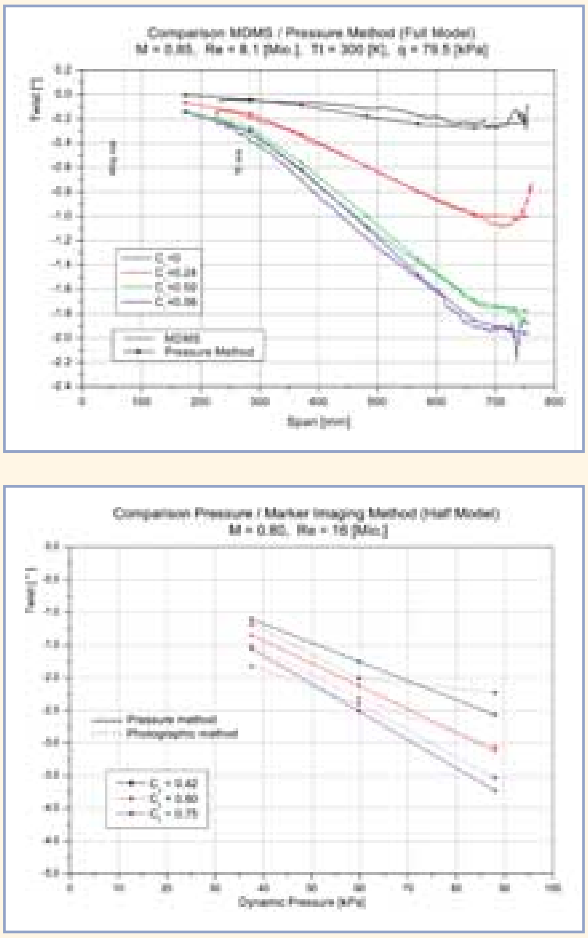


Figure 20:
Above: Wing twist of a full Modell determined with MDMS and Pressure Comparison Method
Below: Twist of a Half Model Wing Tip determined with pressure Comparison Method and Luminescent Marker Imaging Method

The main features are:

Method	Model Requirements	Deflection Information	Applicability
MDMS (Model Deformation Measurement System)	Non-shiny surface	Bending and twist inside an area ≈ field of view of the camera	Full models
Wing pressure comparison	6-8 pressure taps per wing section	Twist as function of C_L and q at each measured section, bending estimate	Full and half models
Luminescent marker imaging	Inserts with luminescent paint in the wing tip (or flap track fairing)	Bending and twist at the wing tip (or flap track fairing)	Half (and full) models

In addition, a videogrammetric technique using paint targets on the wing is under development to provide an alternative to the luminescent marker imaging method for half models with only sparse or no pressure plotting.

Sting Interference Measurement

ETW owns a Twin Sting Rig (TSR) and can offer it with two different measurement techniques from which sting interference effects on lift, drag, and pitching moment may be derived and subsequently applied to the corresponding single sting database.

The first method is the standard twin sting technique, which derives sting corrections from the net measurements on a split rear fuselage.

The second method is the 'Enhanced' twin sting rig (ETSR) technique which derives sting corrections from the net measurements on the complete model by using twin six component balances (**figure 21**).

An example of the drag increment repeatability is shown in **figure 22** for both low and high Reynolds number conditions. These drag increments result from the difference between the measurements of a configuration with a distorted afterbody/sting cavity/dummy sting and a configuration with a full afterbody without a dummy sting. From these figures it can be seen that the general level of uncertainty attained with the ETSR technique is better than one drag count irrespective of Reynolds number, and therefore is of a similar order of magnitude as that achieved in the single sting test series.

4.4 Model Design and Manufacture

Considering the test section dimensions (width 2.4m, height 2.0m), the wing span of transport aircraft configurations should not exceed 1.56m for full models and 1.3m for vertically mounted half models. For com-

Figure 21: Enhanced Twin Sting Rig

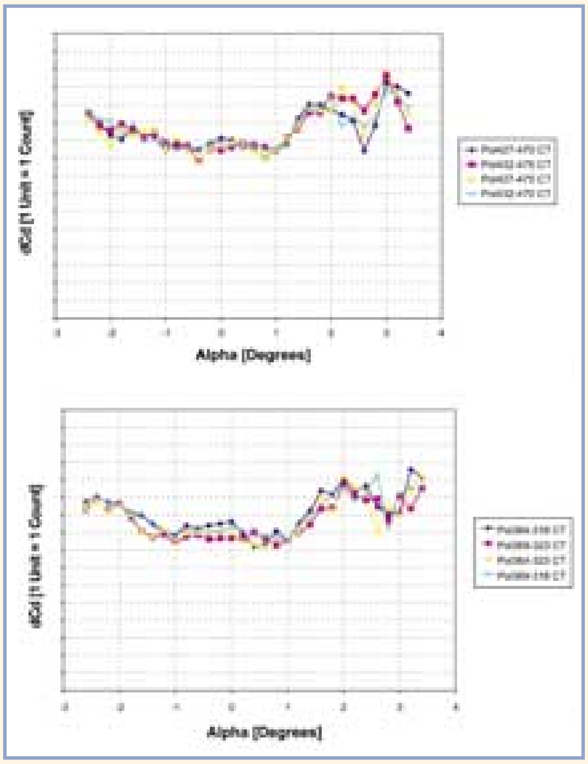


Figure 22: Drag Increments Measured with the ETSR Technique

bat aircraft models, the corresponding values are 0.85m and 0.7m, respectively. The details on model sizing, design details, materials, fasteners and the overall safety procedure is provided in the ETW Model Design Handbook (ETW/D/95004 Revision A) and in the ETW Materials Guide (ETW/D/95005) which will be provided to prospective clients upon request.

The development work for models suited for ETW's cryogenic environment started as early as 1979 and the first ETW models were built in the period of 1989 to 1994 including very detailed studies of materials, fasteners, instrumentation, coatings, handling, fabrication, etc.. These first models were successfully tested in the early campaigns of ETW and since then vast experience has been gained.

Nowadays, model design, manufacture and test preparation of cryogenic models entails only slightly more effort than that for conventional models. ETW can provide model material forged to the main dimensions of the wings and fuselage in a similar cost range to normal high quality steel. The required bolts and screws have been intensively tested and can be provided by several companies. Model manufacture time is normally in the order of 4 to 6 months, depending on the complexity of the model. Pre-design work is typically completed by the client. ETW has contacts with model manufacturers who can also provide detailed design work. During the design period, ETW provides advice to evaluate critical components and handling techniques.

In order to optimize model configuration changes, it is necessary to discuss the individual changes in detail with ETW specialists. Spending additional design effort to suppress bolt heads at the model surface sees immediate benefits during the configuration changes. As significant time can be saved during these handling procedures by avoiding extensive filling and grinding exercises, the overall test campaign cost can be minimized.

The required surface finish of the models is determined by the client taking into account the test objectives and test envelope. ETW is able to provide detailed information to assist in defining the final surface finish for the model. As a general guideline, a model surface with laminar flow requires a surface finish of less than Ra = 0.2 µm, if tested up to a Reynolds number of 40 million.

4.5
Test Assembly

The selection of the final test assembly concerning the model (full span model or half span model) and its support system (performance balance, drag measurement, measurement of model components, straight sting, 2.5°-sting, 5°-sting, etc) is the client's decision in accordance with the envisaged test objectives.

ETW provides the model cart unit, the sting supports including the sting balances, the half model balance support system and the instrumentation involved in the test assembly. It is therefore necessary to discuss all requested equipment and the interfaces in detail at the start of the test campaign planning process in a 'kick-off' meeting.

An overview of information concerning the available support systems and instrumentation is provided in Section 6.

4.6
Test Preparation

The final test preparation of the model and the instrumentation is performed at ETW in one of the Model Preparation Rooms. The client personnel are supported by ETW staff with the mechanical assembly work. Model instrumentation is installed by ETW personnel. An overview of the interfacing components is provided in Section 6. The details need to be discussed with ETW during the client's model design.

The selection of bolts needs to be discussed with ETW specialists. The design details can influence the time for a test campaign significantly. It is important to optimize the design of bolt heads and the required filling holes in order to save handling time during configuration changes. ETW provides filler and sealing materials as listed below:

- Cerrobend is a fusible alloy used for larger holes.
- Two component filler materials selected for cryogenic conditions are used for smaller holes.
- Two component epoxies are typical gluing material for transition bands.
- Xantoprene is a typical sealing material.

The experience gained with these materials and the individual application methods will be provided to client personnel during training familiarization sessions with ETW specialists.

4.7
Model Handling Procedures

ETW is certificated according to the international quality standard EN ISO 9001:2000. The relevant procedures concerning model handling activities are strictly adhered to during model assembly. The following procedures are standard during assembly:

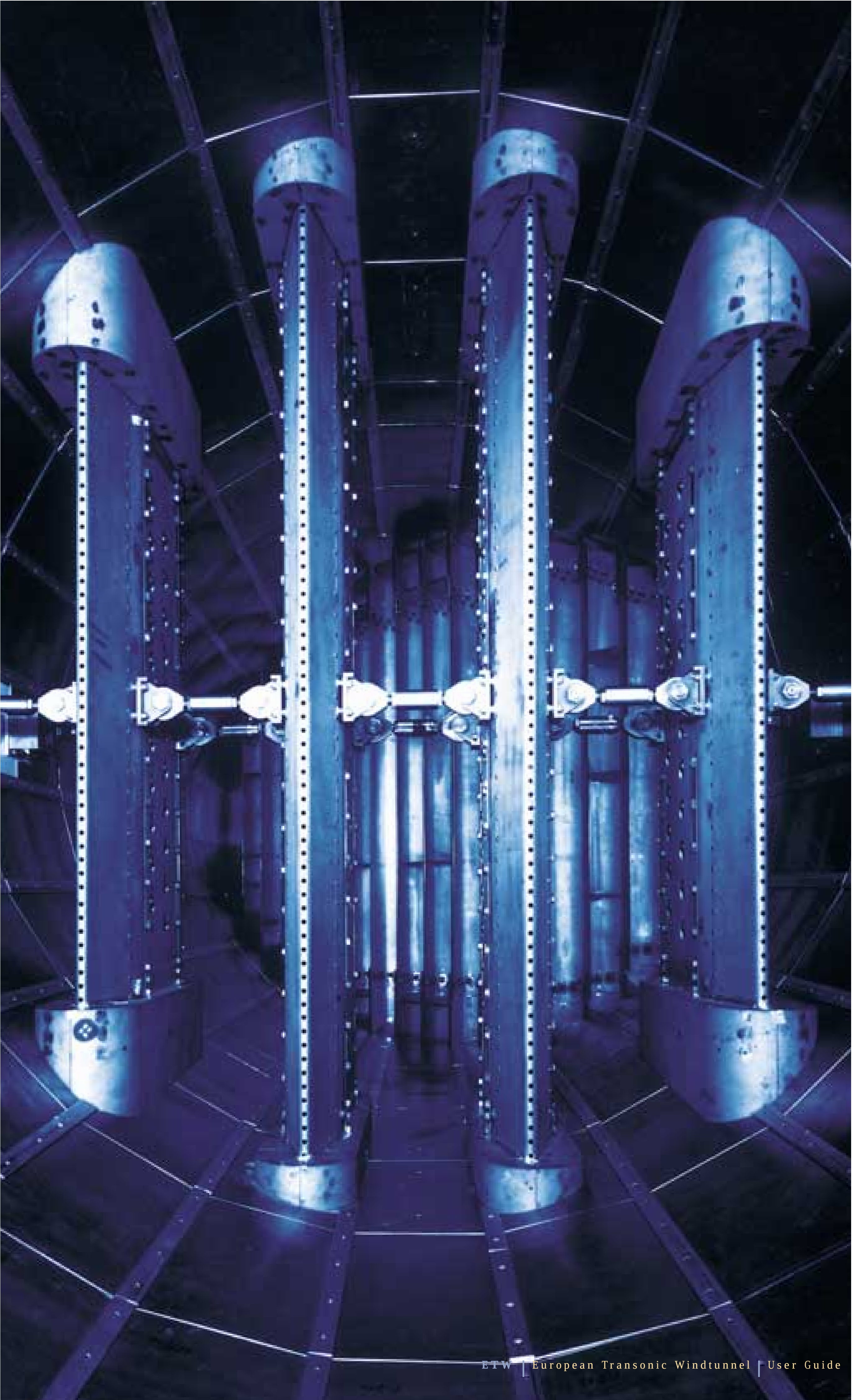
- Bolt torque sheets defining the bolts used, the quantities, size, required torque values, locking method, and any special treatment.
- Model inspection sheets for listing of incidents occurring during the test run.
- Model/balance misalignment sheets with definition for measurement of mechanical misalignment and electrical offset for any inclinometer used in the test assembly.
- Optical identification forms to verify the observation of test assemblies.

These forms are used by the responsible test engineer in close co-operation with the client model rigging personnel.

Further quality checks are performed on special applications. Transition band quality is checked carefully prior to and after each test run. In critical cases the density of the used particles is defined with a counting method to identify the particle density per mm2. This guarantees the high quality and repeatability of transition bands used on the model.

Filling methods require special treatment of the bolt-holes. A mechanical anchoring is necessary if Cerrobend is used. Due to severe pressure changes in the test section, any enclosed air has to be avoided to ensure that the filling stays inside the hole.

Surface roughness measurement is a standard procedure prior to any high Reynolds number test campaign. A careful inspection of the critical surfaces of the model both prior to and after the test runs guarantees a high quality measurement.



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5

MODEL DATA AQUISITION AND DATA PROCESSING

5.1
Model Data Acquisition

The fact that ETW is a cryogenic wind tunnel has only a limited impact on the Model Data Acqusition system (MDA). A more important aspect is the ETW concept of using moveable model carts, comprising the model, model support, test section top wall and an Instrumentation Cabin (IC), so each model cart has therefore its own MDA system and directly related instrumentation. This concept allows the complete model checkout, including a complete cool down, before a run. As no personnel are ordinarily present in the IC during an actual test run of the tunnel, all data acquisition equipment can be operated by remote control.

A dedicated computer located in the Instrumentation Cabin controls each MDA system. For security reasons a dedicated fibre optic cable links it to the MTCR and the dedicated data reduction computer, which is located in the User Room assigned to the client. ETW's computer network incorporates a great amount of flexibility in accessing different systems and files from various locations. It can be reconfigured physically and logically to meet the requirements of a particular test by means of junction boxes and star couplers. **Figure 23** shows the part of the network relevant for the MDA function.

Much attention has been paid to data security and confidentiality. The access control mechanism (passwords etc.) of the VMS operating system is fully exploited. Data disks and tapes can be removed and stored in a safe, and opto-fibres are used for sensitive links to reduce the risk of tapping. If necessary, all computers including the MDA can be physically disengaged from the network and operated in stand-alone mode.

An important criterion for each run of the wind tunnel is productivity so that data rates, and quality and integrity must meet the highest practical standards to minimize the cost per polar. This implies for the MDA that computers are controlling all activities during a wind-on test (e.g. start/stop of model traverses, change of tunnel conditions, camera acquisition and dynamic data capture), allowing the operator to fully concentrate on the monitoring of the test progress and to respond to critical situations.

Acquisition rates can vary from 0.01 Hz (survey mode at night) to 20 Hz, the latter being used for special investigations. Typical data rates for productive wind-on polars are 5 Hz for autonomous transducers and balances, and 1 Hz for Multiport Pressure Systems. The analogue filters in the instrumentation amplifiers are usually set to 1 Hz; they are superior to any numerical averaging. The MDA therefore stores all signal data directly as measured. Higher frequency data can be handled using analogue RMS-converters for real-time purposes (e.g. accelerometers). Another option are MDA controlled data captures with the High-Speed Dynamic Data Acquisition System (HSDAS).

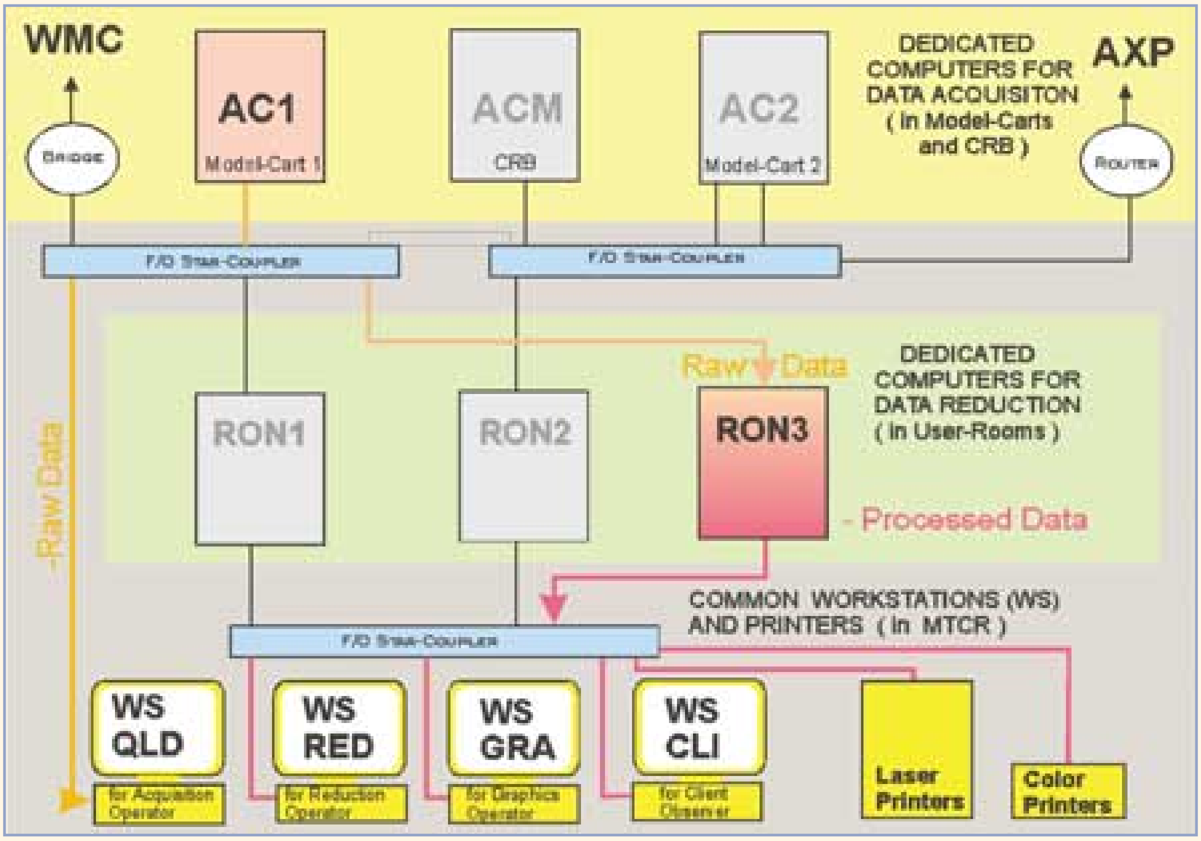


Figure 23: Model Data Aquisition Network Schematic

In more detail, the MDA software performs the following tasks:

- Integrates all model-related instrumentation and control systems, i.e.
  - General-purpose signal conditioning equipment (DAS, CU, RMS; see 6.2.1),
  - Flow Reference Systems (FRS; see 6.2.4),
  - Multiport Pressure Systems (MPS; see 6.2.5),
  - Controllers for heated boxes.
  - Controls and monitors the model position.
- Integrates special acquisition systems like cameras and high-speed (dynamic) data sytems.
- Groups the data of one data-point into records and transfers them to the dedicated Model Data Reduction (MDR) system for data storage.
- Makes all data accessible to the operator in real-time (see below: quick look display).

Additional tasks during wind-on testing are:

- Communication with Windtunnel Main Control (WMC) and monitoring of tunnel conditions.
- Synchronization of data acquisition and model positioning to tunnel conditions, including the start/termination of polars.
- Triggering of special acquisition systems (cameras, high speed systems) at pre-defined tunnel and model conditions.
- Monitoring of selected signals and triggering of actions if predefined thresholds are exceeded (e.g. "fast model home" in case of high accelerations).

All acquired data are identified by names that are assigned according to client's specifications. Supporting information (e.g. coordinates in the model or tunnel coordinate system) is integrated. Instrumentation settings (e.g. gain-, excitation- settings) are monitored and recorded. The various signals are available as raw values (e.g. voltage) and in engineering units, if calibration coeffcients are known. This feature has proven to be very useful in all instrumentation and model checkout activities.

The MDA software allows data visualisation in various formats (e.g. tabulated output, time charts, bar graphs, X-Y plots) in all locations where it is required (e.g. model preparation => next to the model, wind-on test => in the Main Tunnel Control Room).

As not only raw data are sent and stored at the MDR, but also all relevant information required for the interpretation of the acquired data (gains, calibration coefficients, supply voltages etc.), a complete reprocessing can be performed at any time. Operator input such as serial numbers or model configurations can be included in a data point for identification purposes. This concept ensures that raw data, in situ calibrations, and software standards are fully traceable in time and version.

Another important function of the MDA software is the incidence and roll angle control of the model support mechanism. During model preparation and checkout, the commands to position the model are manually entered by the operator. For wind-on tests the complete sequence of tunnel conditions and model traverses is prepared offline as a polar control program, which is subsequently automatically executed and performs all data acquisition and model control functions for a complete run.

Model movements of the following types can be defined in a polar control program:

- **Continuous incidence traverses** with selectable pitch speed (typical: 0.25°/s for pure force measurements; 0.1 to 0.15°/s if combined with pressure measurements).
- **Pitch/pause incidence** traverses with selectable step size and acquisition interval (typical pitch speed: 0.3°/s, pause duration two to five seconds).
- **Side slip traverses** (in pitch/pause mode, requires combined sector pitch and roll movements).
- **Roll traverses** to change from fin-up to fin-down position.

Automatic execution during wind-on includes the following actions:

- Waiting for the requested tunnel conditions to become steady (Mach, total pressure and temperature).
- Positioning of the model at the requested start position.
- Control of the model traverse (including prediction and compensation for sting bending and lift induced up-wash).
- Switching between productive and survey data acquisition mode (e.g. pitch/pause polars).
- Movement of the model to a safe position after the end of a polar or when required by model loads or dynamics.
- Communication with and scheduling of otherwise independent systems like cameras, high-speed acquisition and model deformation measurement systems:
  - Supply of identification data (e.g. Polar-, Datapoint Number, Mach, total pressure).
  - Triggering on selected model and tunnel conditions.
  - Suspension of model movement while these systems are collecting data.

Other test specific data systems can be integrated in a similar way, but need adequate preparation time depending on the requested communication protocol (currently preferred: RS232).

5.2 Data Processing

A data reduction computer running under the operating system OpenVMS is located in each of the User Rooms. It is dedicated to the client throughout the campaign and performs data storage and data processing. The data are exclusively stored on an external disk, which can be dismounted and stored under the control of the client. A cartridge tape drive is also attached, so that backup of the test data and safeguarding of the tapes are performed locally.

The client has direct access to the data reduction computer from his User Room. Immediately after the end of each polar, preliminary test results are already accessible through ETW's software tools, which may be used by the client himself or operated by an ETW staff member upon request. Printers in the User Room and in the MTCR allow printing and plotting of the test data.

During a wind tunnel run, when the client has access to the MTCR, online data is displayed on a number of monitors as numerical and graphical output. If so desired, immediate analysis, including the comparison with results of previous runs or test campaigns, can be performed in parallel.

5.2.1 Data Reduction

The standard data reduction program "PolProc" performs the conversion from signals to physical units, the computation of flow parameters, loads, coefficients, etc. and the application of corrections. It can operate in real time, synchronized on polars, or in an interactive mode. Although it works with predefined arrays for each transducer category, specific requirements can be satisfied by means of predefined files which are included during program compilation.

The quantities of the raw data file are assigned to the program internal array elements using Input Selection Tables (**see figure 24**), thus enabling the program at run time to read the measured data from the file. The results computed by "PolProc" are written to the results data file using the parameter names as specified in the Output Selection Tables. Control information such as processing options, additional or modified transducer definition data and model constants is taken from a Constants Set. The key element of this concept, however, is to store all definition data, i.e. transducer excitation voltage, calibration coefficients, transducer location, etc. in a block preceding the measured values of each polar in the raw data file. Since the definition data are read by the reduction program and automatically linked with the measured quantities, an excellent integrity and traceability of the test data is obtained.

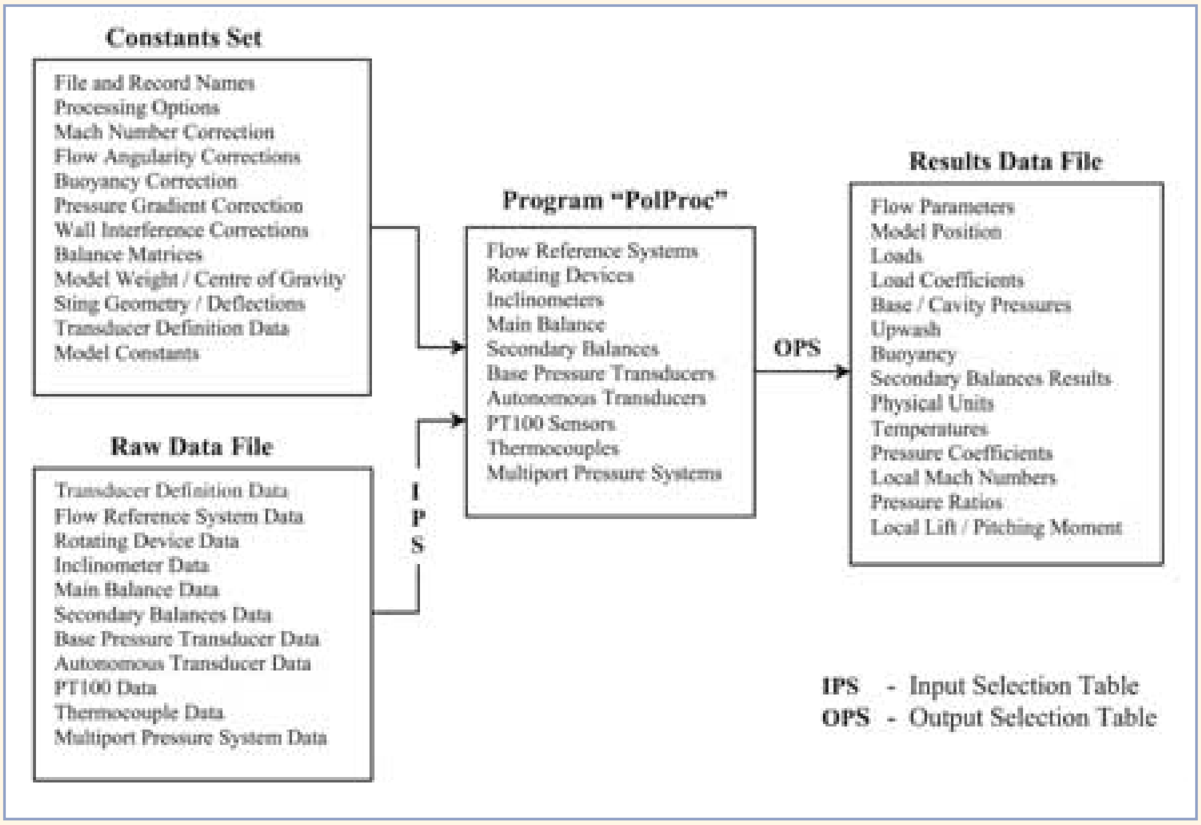


Figure 24: Data Reduction Schematic

5.2.1.1
Computation of Flow Parameters

The flow parameters are computed from the data of two Flow Reference Systems (FRS) using the temperature information plus the measured pressures. Each FRS contains two absolute and two differential pressure sensors of different ranges and accuracies. The data reduction program uses the values of the two most accurate transducers available for the pressure level being measured.

For special purposes, an option exists to define the data of certain other pressure or temperature transducers as reference values.

5.2.1.2
Determination of the Model Position

In the case of single and twin sting mounted models, the reference incidence angle is usually measured by an internal inclinometer, whereas the roll angle information is supplied by a resolver in the sting boss. In addition, the incidence angle of single sting models is calculated from model support data, sting geometry data and deflections under load.

If the enhanced twin sting rig is used, the information of two further inclinometers, installed close to each boom balance, is required to determine the balance positions and transform the balance loads into the model coordinate system.

The incidence angle of half models is derived from the measured angle of the turntable together with the calculated deflections of the balance under load.

5.2.1.3
Computation of Model Loads

The signal offsets of the balance are computed from "wind-off" data by multiplying the known balance loads with the calibration matrix of a given balance temperature. After subtraction of the offsets from the balance signals, the gross loads are calculated using the relevant balance matrix. From the balance gross loads the model weight components are subtracted to obtain the aerodynamic loads and coefficients, which are transformed into various coordinate systems and subsequently corrected for base/cavity pressure, buoyancy and wall interference effects.

5.2.1.4
Processing of Autonomous Transducers

The processing of temperature sensitive, absolute or differential autonomous transducers, resistance temperature sensors (Pt100 type) and thermocouples is also a standard feature of the data reduction program.

5.2.1.5
Processing of Pressure Transducers

For the transducers of all Multiport Pressure Systems, the pressure coefficients, local Mach numbers and pressure ratios are calculated per data point; pressure coefficients are optionally averaged for each data point of pitch/pause polars. In the case of pressure plotted models with a sufficient number of chord wise taps, the pressures of each evaluated wing section can be integrated for an assessment of the local normal force, lift and pitching moment coefficients.

A hydrostatic effect correction as well as an offset/sensitivity correction can be individually applied to each pressure transducer, irrespective of its type. The consideration of test section pressure gradients according to the stream wise position of the respective pressure tap is also possible.

5.2.1.6
Corrections

ETW has worked out an extensive set of corrections covering all types of models and model/sting combinations:

- The residual pressure gradient in the empty test section plus the pressure gradient due to the presence of a certain sting affect:
- the static pressure at the model reference centre used to derive the reference Mach number,
- all pressures measured on and inside the model, including base/cavity and split plane pressures,
- the model drag due to buoyancy.
- Wall interference corrections cover:
- model blockage,
- angle of attack,
- pitching moment,
- wall induced buoyancy drag.
- The flow angularity and curvature are determined and repeatedly checked in the course of each test.
- Base/cavity pressures are normally measured by dedicated transducers fully synchronized with the balance signals. The resulting corrections are applied to the computed model loads.

5.2.2
Post Processing

5.2.2.1
Test Summary Tables

For each test campaign a summary table is maintained and constantly updated which lists the principle characteristic parameters of a polar. However, since each quantity of the results data file produced by the reduction program may be included, additional summary tables can be created covering a wide band of specific requirements.

5.2.2.2
Data Interpolation and Differencing

A program performing a two-parameter interpolation, typically the angle of incidence and the Mach number, can be used to evaluate the model characteristics for a required nominal stationary condition, e.g. the Mach number might be interpolated to 4 significant figures (e.g. 0.7500). The degree of the interpolation polynomial is selectable between 1 (linear) and 5, however the program switches to a lower degree if the specified interval does not contain sufficient measurement points.

After interpolation, the differences between several data sets can be calculated by additional software, which has proven to be a powerful tool especially for the analysis of Twin Sting Rig data. It also allows the computation of averages, standard deviations and maxima/minima.

5.2.2.3
Integration of Third Party Test Data

Upon request by the client, special software can be developed for the conversion of test data originating from a different source into the format used at ETW, thereby allowing the use of ETW owned on-line and post processing programmes.

5.2.3
Data Presentation

Test data can be presented in numerical or graphical form. The respective programs use a largely identical command syntax and are at the client's disposal. However, if the client prefers to use his own analysis and presentation software, the data can be transferred to his computer shortly after the test run. In addition to some special data formats (e.g. TecPlot), a simple ASCII format compatible with most spreadsheet programs is offered as a standard option. However, flexibility of data arrangement and format also allows an easy adaptation to individual requirements.

5.2.3.1
Numerical Presentation

The program for producing tabulated output allows the definition of an individual format for each quantity, a quantity header different from the quantity name and a unit denomination. The page layout (number of rows and columns) is adaptable to any paper format.

5.2.3.2
Graphical Presentation

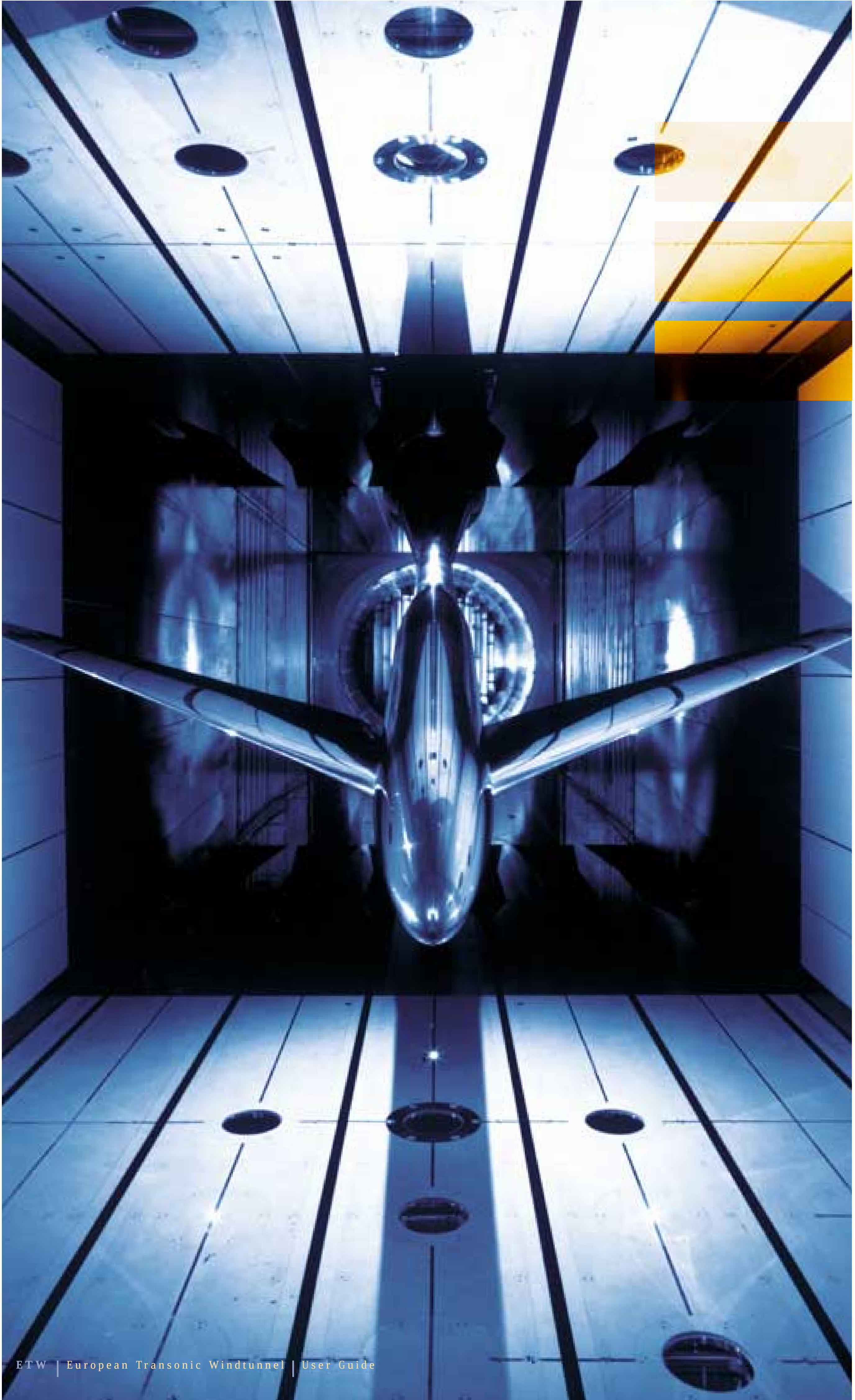
The graphics tool available at ETW can be used for real-time data display and off-line plotting. The main features are:

- Presentation of purely dynamic data (e.g. C_L vs. α) or combined static and dynamic data (e.g. C_P distribution vs. tap location).
- Flexibility in combining data from different polars and data files, including raw data, interpolated data, and results obtained from differencing.
- Legend information derived directly from the data file.
- Variable plot layout.
- Quick and easy access to reference polars.
- Rapid generation of complex plots through use of control files.
- Data point selection according to an arbitrary selection criterion.
- Staggering option.
- Automatic identification of available printers.
- Mathematical operations on and between selected quantities, including curve fits.

Some examples of plot layouts and output styles are given in **Appendix 1**.

6

TEST SYSTEM DETAILS



6.1
Model Supports

6.1.1
Model Carts

		Model Cart 1	Model Cart 2
Distance from Point of Model Rotation to Model Cart Flange	mm	2,296	3,097
Pitch Range	°	-10 to +35	-10 to +20
Roll Range	°	± 190	± 190
Pitch Rate	°/s	0.05 to 2	0.05 to 2
Roll Rate	°/s	0.05 to 10	0.05 to 10

Table 1: Characteristics of the Model Carts

To meet the productivity and confidentiality demands of the aerospace industry, ETW is designed to operate an interchangeable model cart system. Two model carts are available for sting mounted full span models one of which can be modified to accept vertically mounted half models. A cart with a sting mounted model is shown in **figure 25**.

6.1.2
Half Model Facility

A half model testing capability is provided by an exchange of the slotted test section top wall of Model Cart 1 with a solid half model top wall including a turntable and an external five-component balance.

Pitch range ± 45 degrees
Pitch rate 0.05 to 1 degree/sec.

A typical half model attached to the model cart is shown in **figure 26**.

Figure 26: Half Model in High Lift Configuration

Feasibility studies and preliminary tests have been conducted for a high-pressure gas supply system to enable, in the future, Turbine Powered Simulation (TPS) with half models.

6.1.3
Stings

ETW owns a collection of different sting supports with various design concepts and joints. Straight stings for 0° and 2.5° attachment, Z-sting and fin-sting components, twin sting support and several adapter pieces are available as summarized in **Appendix 2**. A sting geometry with low interference has been

Figure 25: Model on Straight Sting in Test Section

developed with special attention to sting divergence. During model design the bending of the balance and sting is critical to the required gap between the model fuselage and sting. Detailed computation and careful selection of the tunnel test envelope is therefore necessary for an optimized model design.

Individual adaptation or special design and manufacture of particular supports and stings for clients' models is possible in co-operation with ETW.

6.2 Instrumentation

6.2.1 Balances

The ETW balances are listed in **Appendix 3** giving details on dimensions and loads. Different joints are available. The standard ETW internal performance balance has a flange with 100 mm outer diameter. Taper joints are also available to allow installation in smaller fuselage diameters.

For half model testing, an external balance is attached to the respective top wall structure of the model cart. The layout and load ranges are given in **Appendix 3**.

6.2.1.1 Balance Calibration Facility

A novel automatic Balance Calibration Machine (BCM) has been developed and is used for calibrations of all ETW balances. The machine is designed to cover the complete temperature range of the facility. The BCM is also available for calibrations of clients' balances. It offers the possibility to apply an arbitrary number of components simultaneously, to calibrate a balance over realistic multidimensional operating parameters.

The load ranges for the different components have been adapted to those of the transport aircraft performance balances and are given in **table 2** below. The accuracies stated reflect the differences in importance of the aerodynamic coefficients.

6.2.2 Model Attitude Measurement

The precise determination of the drag and lift coefficients in the wind axis system requires that the model angle of attack is known with an accuracy of 0.01 degree. Like most other advanced facilities, ETW relies on a classical gravity vector sensing servo-accelerometer.

ETW equips each model with a Sundstrand Q-Flex inclinometer mounted in a vacuum insulated, heated box. Several versions of the heated box are available. A larger one contains a Q-Flex, two electrolytic bubbles (model erect and inverted) and a tri-axial accelerometer. The latter can be used for model vibration monitoring, and also for centrifugal acceleration compensation. The mounting base is made of low-expansion carbon fibre material to avoid distortions due to temperature gradients. The small heated box, intended mainly for fighter model applications, does not have the electrolytic bubbles.

A special Inclinometer Conditioning Unit (ICU) directly computes the angle in thousands of a degree. Amplification, filtering and analogue to digital conversion are adapted to the wind tunnel environment. Special circuitry allows a partial compensation of centrifugal acceleration errors, using Z- and Y-axis accelerometers as inputs.

Each MDA system includes four ICUs to enable conditioning of Q-Flex inclinometers that are installed in other locations, i.e. the sector and top wall.

Component	Nominal	Max.	Accuracy	Resolution
Normal Force	20,000 N	25,000 N	4.0 N	0.40 N
Side Force	3,000 N	3,000 N	1.5 N	0.15 N
Axial Force	1,500 N	2,000 N	0.3 N	0.03 N
Pitching Moment	1,200 Nm	1,500 Nm	0.4 Nm	0.04 Nm
Yawing Moment	1,000 Nm	1,000 Nm	0.5 Nm	0.05 Nm
Rolling Moment	2,000 Nm	2,000 Nm	1.0 Nm	0.10 Nm

Table 2: Load Ranges and Accuracy of the BCM

6.2.3
Multi-Port Pressure Systems

For multiple pressure measurements, ETW has standardized on the PSI 8400 series of systems. A total of five systems are available, which are allocated as follows:

- Tunnel Hall, Test Section wall pressures
- Model Cart 1, Model & Top Wall pressures
- Model Cart 2, Model & Top Wall pressures
- Cart Rigging Bay, Model Preparation
- Instrumentation Lab, Transducer Calibration

All of these systems can easily be reconfigured to be tailored to a particular application. A large number of plug-in modules with different functions and ranges are therefore available.

After evaluating the performance of the standard PSI system in a cryogenic environment, ETW suggested a number of modifications in the interfacing between the multi-port sensors and the 8400 System Processor. These resulted in a drastically reduced wire count, longer calibration intervals and improved data quality. The present configuration includes a small (ESP size) Scanner Junction Unit, which should be mounted in the vicinity of the sensors. On the System Processor side, a new S84-IFC Unit including a power supply, has been added.

For the model-mounted multi-port modules, ETW has standardized on the PSI high-density electronically scanned pressure (ESP) series with 64 transducers. ETW carries several of these units with ranges from 17 kPa to 310 kPa which are available for client use if required.

Model pressure measurements are essentially differential, so they require a reference pressure, which must be stable and accurately known. As the hydrostatic pressure difference between Instrumentation Cabin and model can be up to 1 kPa, ETW utilizes a high accuracy absolute transducer on the tunnel centreline in the sting boss as a reference.

Needless to say the ESP sensors and SJU have to be mounted in a heated box in a cryogenic model. Special purpose controllers to that end are available.

6.2.4
Flow Reference Systems

ETW has developed special purpose Flow Reference Systems (FRS) for establishing the pressures and the temperatures necessary for calculating the fundamental flow parameters, such as Mach number M, dynamic pressure q, flow velocity V and Reynolds number Re, with the required accuracy. Its data are used both for automatic control of the facility and for data acquisition. Due to this dual-purpose use, two independent IEEE-488 interfaces are provided, each giving outputs in fully corrected engineering units at a sampling rate of 10 Hz.

ETW utilizes three Flow Reference systems. Two are permanently installed in the Tunnel Hall and the third, which also supports remotely located transducers, is extensively used in the Instrumentation Cabin during tunnel calibration and for special tests in the laboratory.

The two FRS systems located in the tunnel hall are used for tunnel operation and are mounted on either side of the test section. To avoid the difficulty involved in correcting hydrostatic errors, both are mounted at tunnel centreline level and use only horizontal pneumatic tubing to the Pt and Ps pressure taps. In order to assure sufficient accuracy and resolution of M and q over the full operating envelope of ETW, three pressure ranges for Pt - Ps are necessary. Each FRS therefore contains four high accuracy pressure transducers: two absolute ones for Pt and Ps, and two differential ones for (Pt-Ps). For measuring total temperature Tt, a very accurate temperature sensor channel is included. Accuracy and resolution details are listed in **table 3**.

Parameter	Range	Accuracy	Resolution	Unit
Pt	100 - 500	.050	.010	kPaAbs
Ps	50 - 500	.050	.010	kPaAbs
(Pt-Ps)1	0 - 140	.015	.002	kPaDiff
(Pt-Ps)2	0 - 40	.005	.001	kPaDiff
Tt	80 - 313	.100	.010	K

Table 3: Flow Reference System Capability

The FRS is an adapted version of the 8400 SP mainframe supplied by Pressure Systems Inc (PSI). The main modifications are:

- Addition of a VME board for temperature measurement.
- Addition of a second IEEE 488 interface.
- Software enhancements.

The system uses high accuracy Paroscientific Digiquartz transducers in the four Pressure Sensing Units (PSU´s).

6.2.5.

Signal Conditioning Equipment

The general-purpose signal conditioning equipment is intended for use with passive instrumentation such as balances, individual pressure transducers, RTDs and thermocouples. Requirements are different for every test, so a large flexibility in every aspect is essential. ETW opted for a modular approach, where even the size of the system (number and type of channels) can be adapted to a particular test. As a rule each channel has its own analogue to digital converter, and multiplexing is subsequently carried out at a digital level. The inherent advantage in this methodology is that there is no time skew between individual data channels, which is a prerequisite for efficient continuous sweep (vs. pitch-and-pause) testing. When addressed, each channel transfers its data to a parallel, high-speed data bus for input into the Model Data Acquisition (MDA) computer.

6.2.5.1

Conditioning Unit

The backbone of the signal conditioning equipment in each of the Instrumentation Cabins is formed by 64 Conditioning Units (CU). A CU performs, in one integrated package, all of the functions required for conditioning and digitizing the signal of a single, high-accuracy analogue data channel. Any number of CUs can be connected to a common digital data bus, allowing configurations of computer controlled acquisition systems of arbitrary size.

The units are completely self-supporting, include a display and can therefore also be used for stand-alone applications. This feature has proven to be very useful in a wind tunnel environment. The functions and respective ranges are:

Excitation Power Supply	0 to 16 V DC
Adjustable Zero Offset	-200 to +200 mV
Instr. Amplifier Gain	1-2-5-...-1,000
Low Pass Filter	1-3-10-...-1,000 Hz, Wide Band
Overload Detection	Peak & Average
Analogue Output	Wide-band & Filtered, Buffered
Analogue to Digital Converter	15 bits (16 bits opt.)
Numerical Display of ADC	-16,384 to +16,383 mV
Floating Input up to ADC	Opto isolators

Table 4: Conditioning Unit Ranges

Two compatible versions of ADC plug-in cards are available. The slow model is a dual slope integration type allowing 20 Hz sampling rate, whilst the fast model is a successive approximation type with a conversion rate of 20 kHz. Since these are the sampling rates per channel, the aggregate rate for a large number of channels can be very high. All manual switching functions can be read out as status data and the calibration or check-out functions can also be remotely activated.

6.2.5.2

Calibration Generator

The Conditioning Units have relays for switching externally generated calibration voltages to the inputs of the Amplifier and the ADC, allowing a complete computer controlled calibration to be carried out. A high precision, high stability Calibration Generator is included in the system for generating the appropriate voltages. This has separate CAL ADC and CAL AMP outputs, the ratio of which, set by a high accuracy voltage divider, represents the nominal gain of the amplifier to be calibrated. The voltage reference source is temperature controlled and has extremely good long term stability. The Calibration Generators are crucial for the accuracy and traceability of the results of the data system. They are regularly calibrated by an accredited laboratory.

CAL ADC output	-11.000 to +11.000 V
Accuracy CAL ADC	+/- .002%
Resolution	1.000 V
Offset	+10 V, 0, -10 V
Vernier (manual)	0 to 1.000 V
CAL AMP voltage divider	1-2-5-10 to 5000
Accuracy voltage divider	+/- .01%

Table 5: Calibration Generator Specification

TEST SYSTEM DETAILS

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6.2.5.3
Multi-Channel Conditioning Unit

For those applications where the primary interest is in the AC component of dynamic signals, e.g accelerometers, acoustic transducers (Kulites) or buffet gauges, a special Multi-Channel Conditioning Unit (MCCU) is included. In a compact 19" rack it provides all essential functions for 16 channels:

Excitation Power Supply	0 to 15 V DC
Adjustable Zero Offset	-100 to +100 mV
High-pass Filters	1 Hz
Separate AC & DC Gains	1-2-4-...-8000
Bandwidth	100 kHz
Line Drive Capability	10 nF
DC Read-out & Display	-16384 to +16383 mV
Low Noise-level	3 µV rms, Wideband
Remotely programmable	IEEE 488

Table 6: Multi-Channel Conditioning Unit Data

The overall accuracy is 0.1%.

6.2.5.4
Multi-Channel RMS Converter

For dynamic signals, the RMS value is of primary interest, therefore, each MDA system includes two 8-channel units with a bus compatible digital output. Its inputs can be connected to the output of a regular CU, a MCCU or any other high level source. If necessary, available high-pass, low-pass or band-pass filters can be included in this link. As typically these signals are of a fluctuating nature, each channel has its own integrating type ADC with variable time base. The following specifications apply:

Bandwidth	1 Hz to 30 kHz
Range	0 to 8,000 mV
Accuracy	.1% at Crest Factor 3
Integration time ADC	50 ms to 5 s
Overload detection	
Analogue RMS Output	

Table 7: RMS Converter Specification

6.2.5.5
DAS Interface

The link between the multi-access signal conditioning data bus serving the above mentioned devices and the parallel input/output (IO) of the acquisition computer is formed by a unit called the DAS Interface. It performs such diverse functions as:

- address decoding into individual strobe signals,
- BCD to binary encoding when necessary,
- command decoding, e.g. for calibration purposes,
- handshaking with the MDA computer,
- opto-isolation of the computer IO signals,
- timing for high speed data acquisition.

6.2.5.6
High Speed Data Acquisition

In addition to the steady state and quasi-dynamic systems stated above, ETW can offer a fully digital High Speed Data Acquisition System (HSDAS) to gather data from fast response transducers.

The HSDAS is a PC-network-based intelligent data acquisition system with 32 input channels and provision for expansion to 64 channels. The unit provides a fully programmable signal conditioning front end with a full range of signal input options including direct voltage and strain gauge with AC or DC coupling. The system is capable of measuring at a sampling rate of up to 100,000 samples per second, irrespective of the number of channels being recorded.

The system is fully integrated into ETW's data acquisition system and is under the control of the High Level System.

In addition to the data acquisition, the system comes complete with its own extensive data analysis and reporting software. Standard processing procedures allow signal manipulation, and analysis and display of the data, all of which can be performed in the time and frequency domain. Extensive interactive graphical tools and analysis automation provide an objective measurement system. Test results can be quickly compared with previous data. The data processing is supported by extensive QA tracking through data history recording, and the use of the integrated Project Manager. The results can be exported in various formats and can, if required, be tailored to suit the client's individual needs.

Analogue Inputs	32 Single Ended, 0-1 mV to 0-10 V
Filter Bandwidth	Up to 26.5 kHz
AC/DC coupling	Programmable Selection
Programmable Gain	1,2,4,8,10..80, 100..800, 1,000..4,000
Programmable Offset	+/- 6V applied after first stage gain
ADC Resolution	16 bits
Sampling Rates	100Hz to 100kHz
Transducer Excitation	0-15 V in 50 mV steps

Table 8: Characteristics of the High Speed DAS

6.2.6
Temperature Measurement Channels

For a cryogenic facility such as ETW, the need for the measurement of a large number of temperatures is self-evident. In principle ETW has standardized on three types of temperature sensors for Data Acquisition Instrumentation:

- Pt 100 RTD
- Type T Thermocouples
- Semiconductor Diodes

Each have their own field of application and their particular signal conditioning.

6.2.6.1
Platinum 100 Resistance Thermometry Devices

Pt 100 RTD's are used where high accuracy and good long-term stability are required. For that reason, the FRS total temperature sensors and the ten sensors on the ETW balances are Pt 100´s. Due to the considerable influence of temperature on cable resistance, ETW uses a four wire configuration per sensor and a high accuracy constant current supply of 1 mA. The latter is created by inserting a special current module in the patch lead on the input patch panel, and measurement is by way of a standard Conditioning Unit.

6.2.6.2
Type T Thermocouples

In principle ETW has standardized on the use of Type T (Copper-Constantan) Thermocouples for those multiple applications where the requirements on accuracy and long term stability are less severe than above. Type T Thermocouples show the most consistent behaviour at cryogenic temperatures. The sector (model support) cabling includes 24 channels of Type T extension wire. ETW favours the use of floating equithermal reference junctions, measuring the temperature of the junctions with a Pt 100 RTD. For on-board use, 10 channel reference junction boxes are available and in each instrumentation cabin a 32-channel reference junction is installed. For low-level voltage measurement, either Conditioning Units or Analogue Input Units (AIU) of the PSI system can be used.

6.2.6.3
Semiconductor Diodes

Their high sensitivity (2,5 mV/K) and their ease of a two (copper) wire connection make Semiconductor Diode Temp Sensors an attractive alternative. They are excited by 10 µA provided by a special current module in a patch lead.

6.2.7
Model Support Cabling

For signal transmission between the Instrumentation Cabin and the Model Support Sting Boss, a large number of different cables are installed in the Model Carts. Their length is approximately 30 m. It should be realized that the resistance of the cold part of these cables (~ 20 m) will decrease considerably compared to ambient temperatures, i.e. will go down from 5.3 Ω to about 2 Ω for a loop of AWG 24. The following cabling/tubing is installed:

Nr. of Cables	Nr. of Wires	AWG	Type, Use	Cross Section mm²	Screen
60	7	24	General	0.22	yes
8	7	24	PSI	0.22	yes
8	6	24	Type T-TC	0.22	yes
9	7	16	Power	1.34	yes
6	1	50	Coax		
6			Pneum. Tube	2 ID, 4 OD	

Table 9: Installed Model Support Cabling

TEST SYSTEM DETAILS

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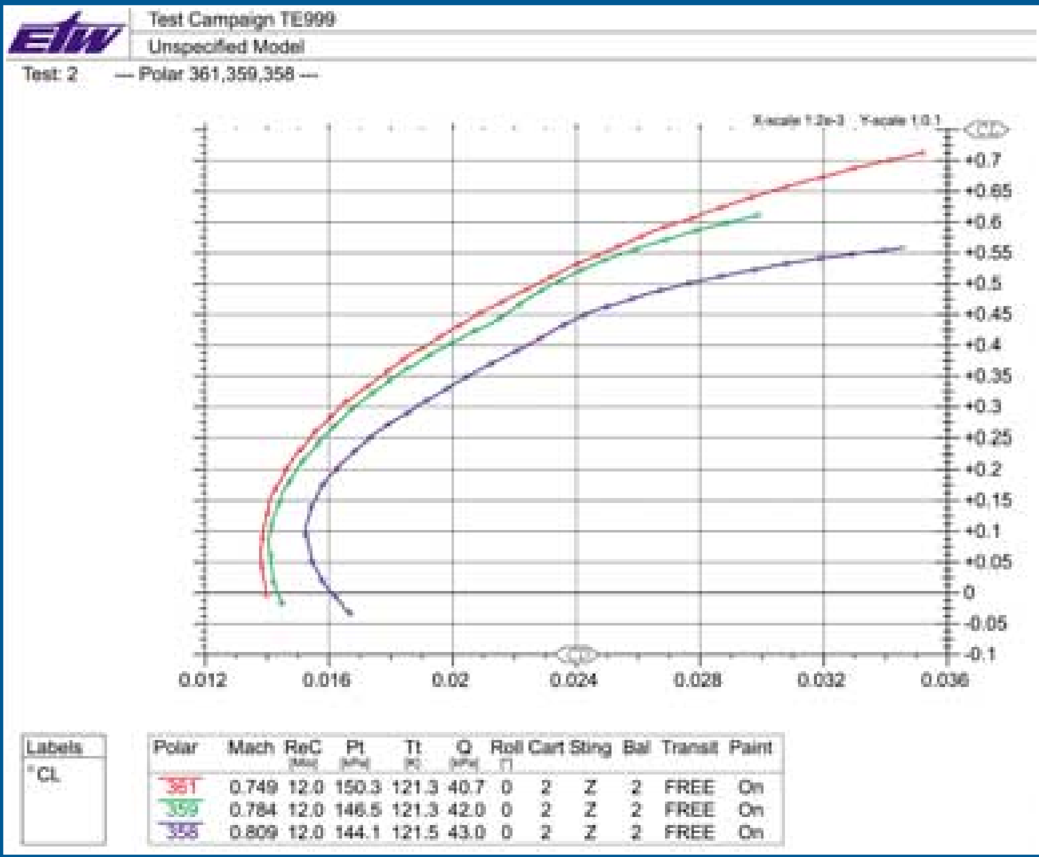
APPENDIX 1
Examples of Plot Layouts and Output Styles for Test Results

APPENDIX 2
Model Support Components (Stings, etc.)

APPENDIX 3
Overview of ETW Balances

APPENDIX 4
List of Abbreviations

APPENDIX



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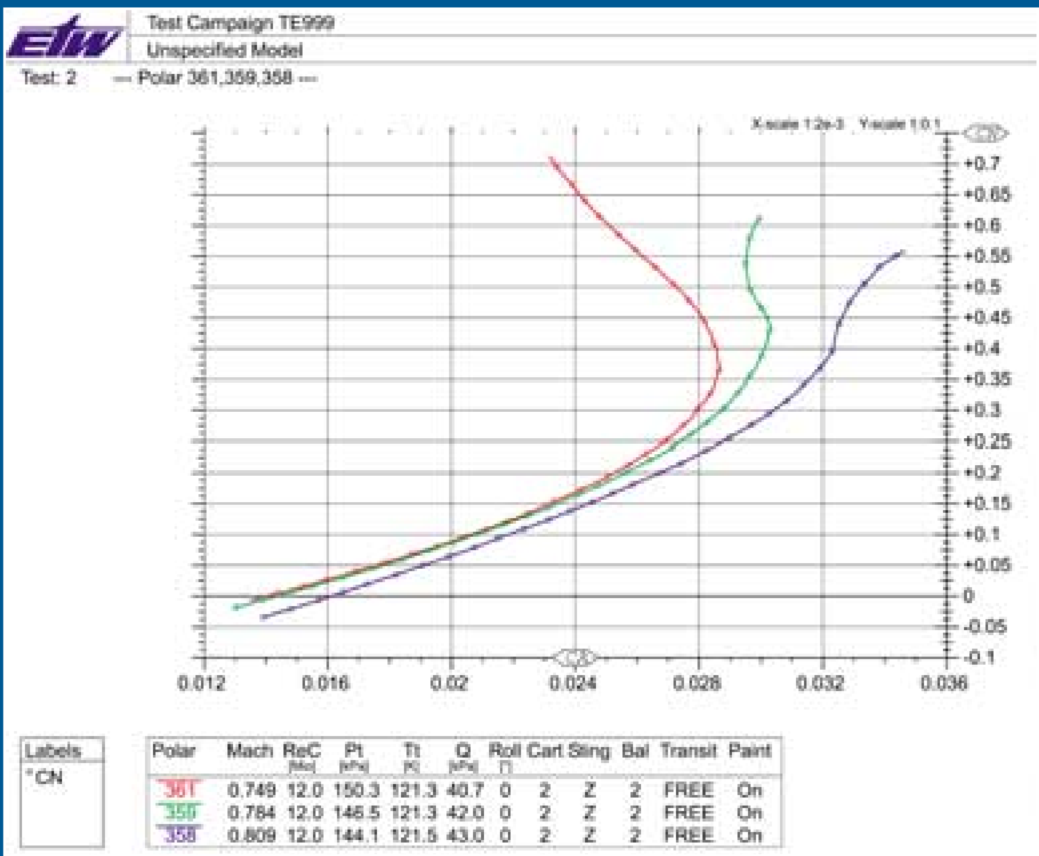

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CN
CA
Labels
CN
Polar Mach ReC Pt Tt Q Roll Cart Sting Bal Transit Paint
361 0.749 12.0 150.3 121.3 40.7 0 2 Z 2 FREE On
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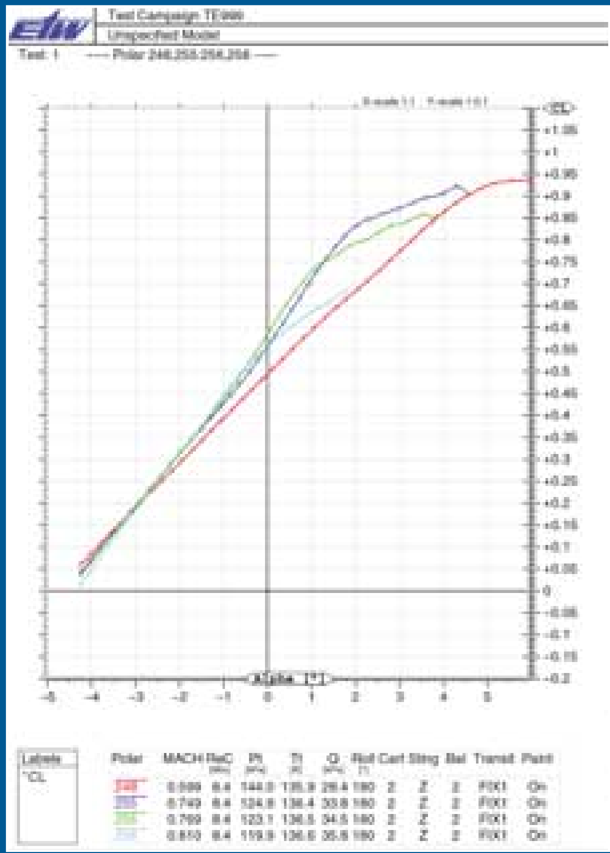
358 0.809 12.0 144.1 121.5 43.0 0 2 Z 2 FREE On

APPENDIX 1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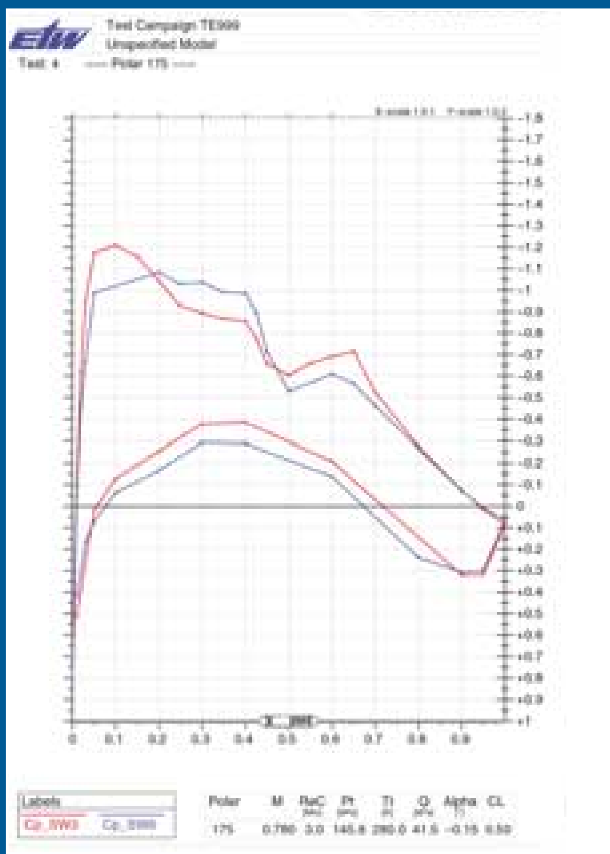
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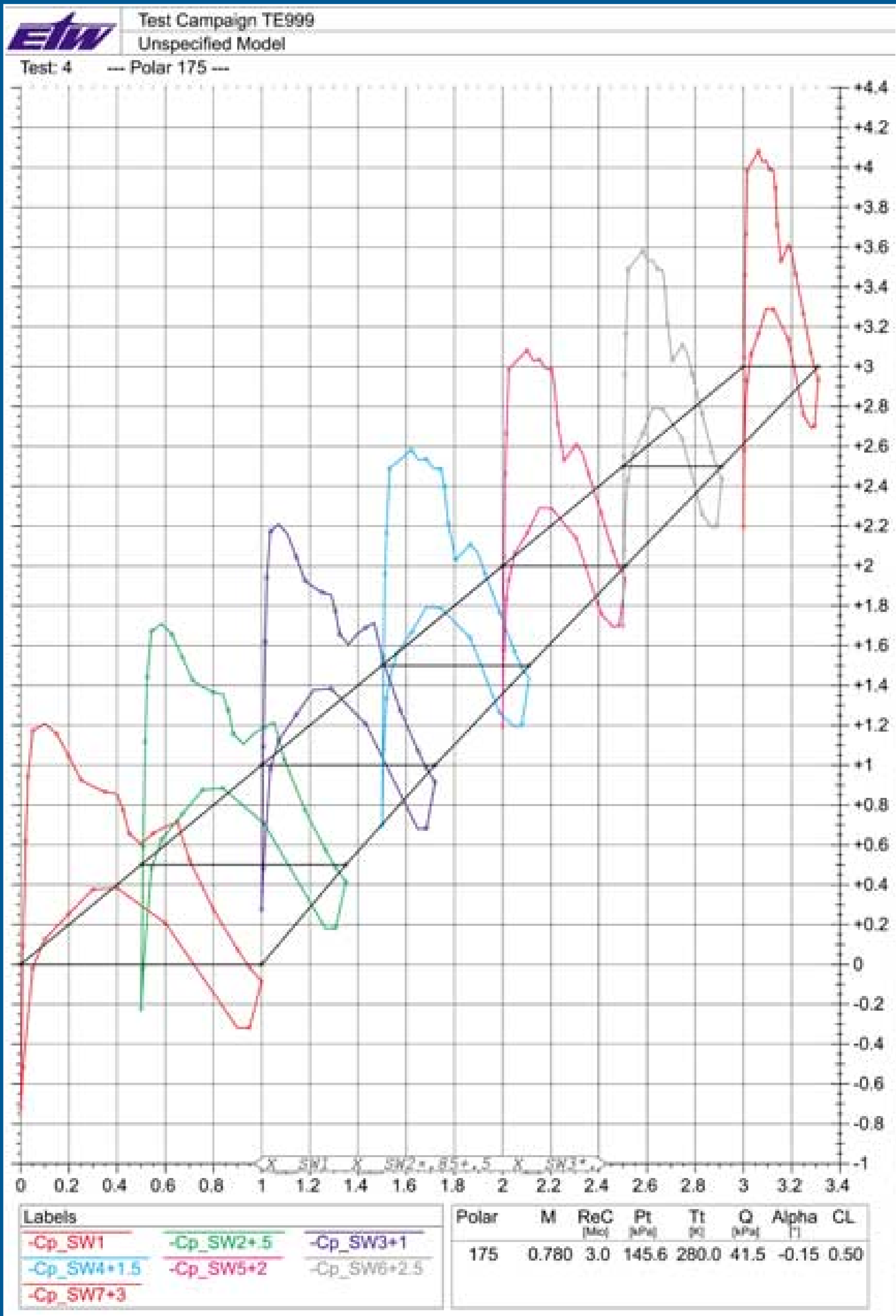
APPENDIX 1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-Cp_SW5+2
-Cp_SW6+2.5
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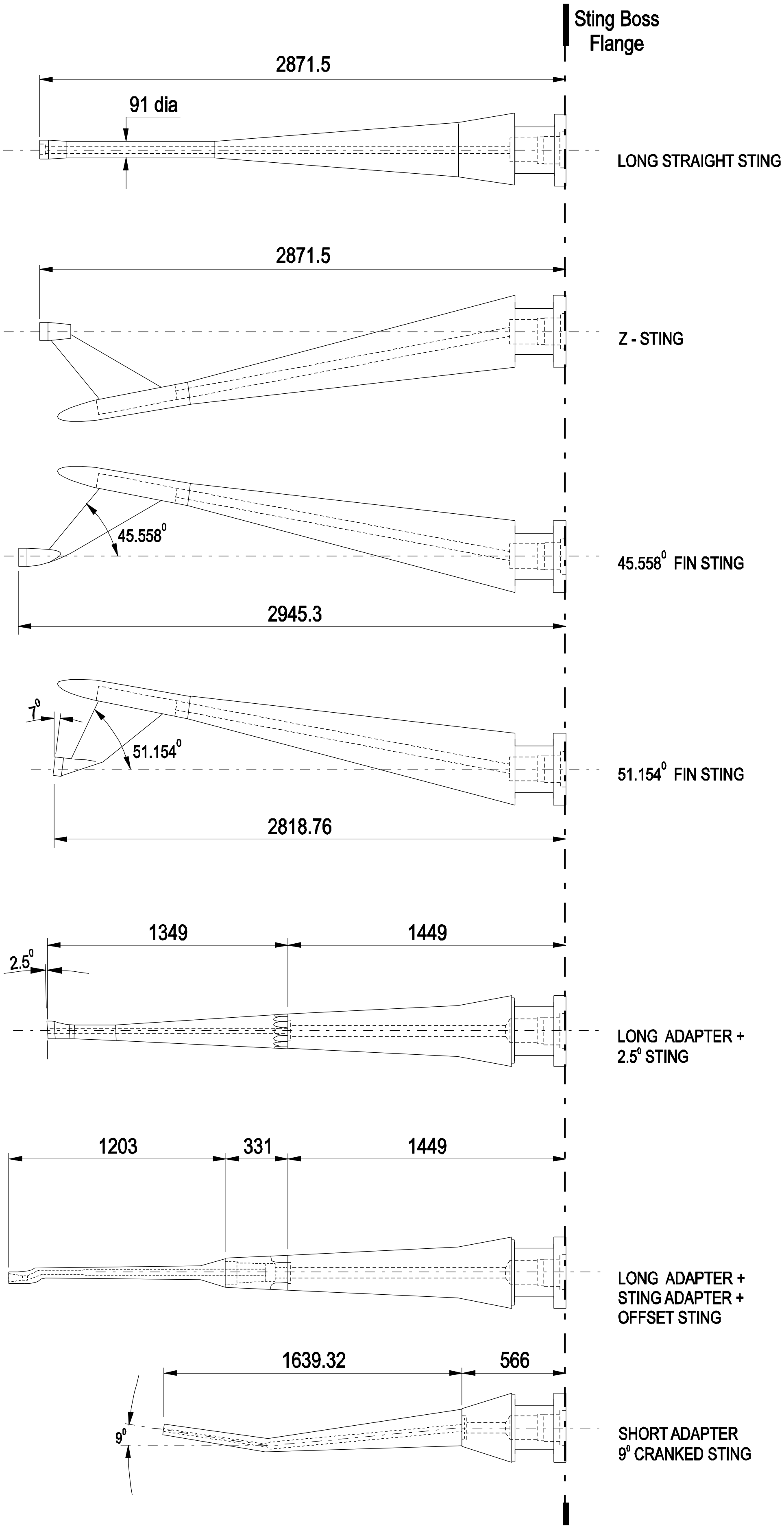
Sting Boss
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2871.5
Z - STING
45.558°
45.558° FIN STING
2945.3
7°
51.154°
51.154° FIN STING
2818.76
1349
1449
2.5°
LONG ADAPTER +
2.5° STING
1203
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STING ADAPTER +
OFFSET STING
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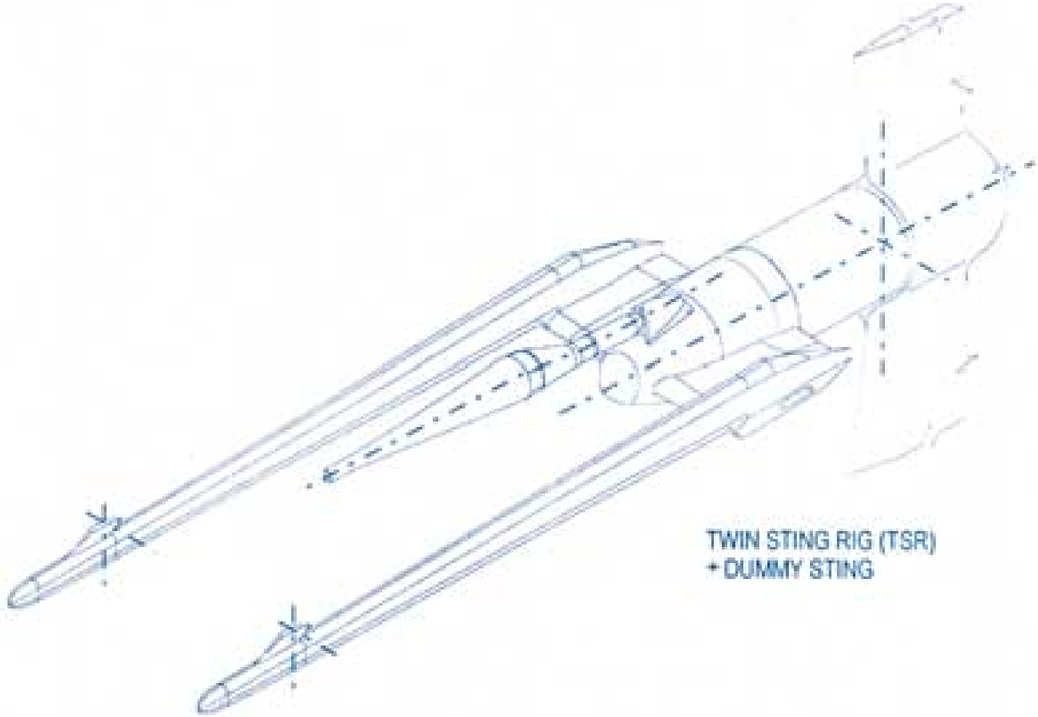
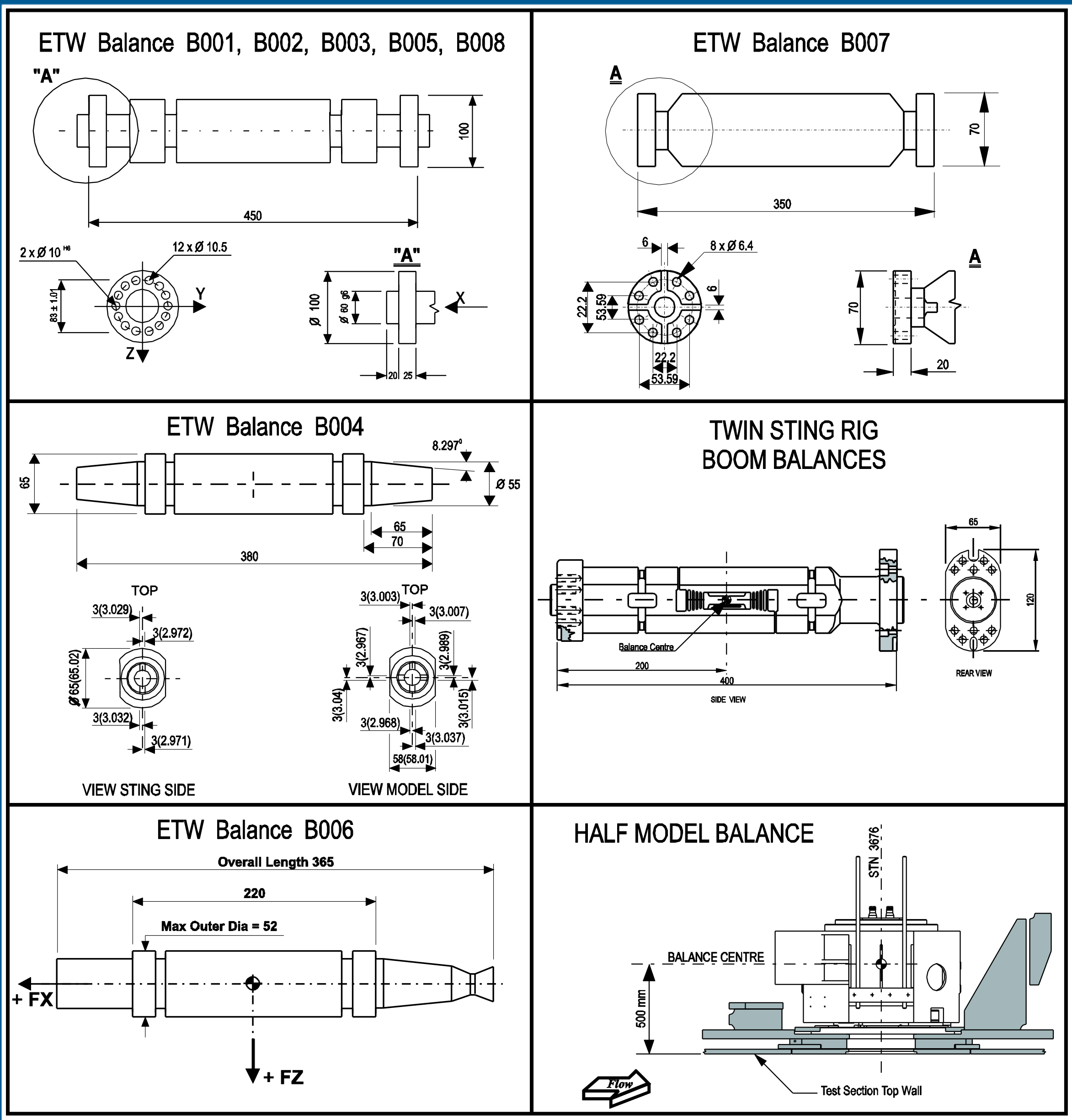
566
9°
SHORT ADAPTER
9° CRANKED STING

APPENDIX 2



APPENDIX 2



Component as Combined Loading / Balance / Material			Maraging Grade 250	Marval 18	Maraging Grade 250	Maraging Grade 250	Copper Berillium	Maraging Grade 250	Maraging Grade 250	Marval 18	Maraging Grade 250
			001	002	003	004 Combat	005	007	008	**TSR Boom Balance**	**Half Model Balance**
Normal Force	[NF]	N	12000	20000	26000	30000	20000	6000	26000	13000	55000
Side Force	[SF]	N	1000	2500	3200	5500	1500	2500	3200	1800	0000
Axial Force	[AF]	N	1000	1500	2000	3500	2000	500	2000	1100	5500
Pitching Moment	[PM]	Nm	700	1200	1500	2500	1250	1600	1500	1300	4400
Yawing Moment	[YM]	Nm	80	150	300	800	180	1200	300	450	3300
Rolling Moment	[RM]	Nm	100	750	1000	800	350	500	1000	450	33000

Component as Single Loading / Balance / Material			Marval 18
			006
Normal Force	[NF]	N	35000
Side Force	[SF]	N	30000
Axial Force	[AF]	N	5500
Pitching Moment	[PM]	Nm	1650
Yawing Moment	[YM]	Nm	650
Rolling Moment	[RM]	Nm	650

APPENDIX 3

APPENDIX 4

List of Abbreviations

AC	Alternating Current
ADC	Analogue-to-Digital Conversion
AIU	Analogue Input Unit
AVS	Anti-Vibration System
AWG	American Wire Gauge
BCD	Binary Coded Decimal
BCM	Balance Calibration Machine
CFD	Computerized Fluid Dynamics
CMOS	Control and Monitoring System
CRB	Cart Rigging Bay
CU	Conditioning Unit
DAS	Data Acquisition System
DC	Direct Current
ESP	Electronically Scanned Pressure
ETSR	Enhanced Twin Sting Rig
FRS	Flow Reference System
HSDAS	High Speed Data Acquisition System
IC	Instrumentation Cabin
ICU	Inclinometer Conditioning Unit
IO	Input / Output
MCCU	Multi-Channel Conditioning Unit
MDA	Model Data Acquisition
MDMS	Model Deformation Measurement System
MDR	Model Data Reduction
MHC	Model Handling Control
MPS	Multiport Pressure System
MTCR	Main Tunnel Control Room
PSI	Pressure Systems Inc.
PSP	Pressure Sensitive Paint
PSU	Pressure Sensing Unit
QA	Quality Assurance
QCR	Quick Change Room
RMS	Root Mean Square
RTD	Resistance Thermometry Device
SJU	Scanner Junction Unit
TCR	Temperature Conditioning Room
TPS	Turbine Powered Simulation
TSP	Temperature Sensitive Paint
TSR	Twin Sting Rig
VMS	Virtual Memory System
VTCR	Variable Temperature Checkout Room
WMC	Windtunnel Main Control

Published by:
European Transonic Windtunnel (ETW) GmbH, Köln

Editor:
Georg Sötsch

Pictures:
ETW, EADS Airbus, Dassault

Layout and Design by:
ziller design, Mülheim an der Ruhr, Germany

Printed by:
Thierbach GmbH, Mülheim an der Ruhr, Germany

European Transonic Windtunnel

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