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TOOLS AND TECHNIQUES FOR HIGH REYNOLDS NUMBER TESTING STATUS AND RECENT IMPROVEMENTS AT ETW

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Abstract

The European Transonic Windtunnel (ETW) is a pressurized cryogenic facility for testing aircraft models up to flight Reynolds number at Mach numbers up to 1.3. This wind tunnel concept requires tools and techniques specially dedicated for the cryogenic test temperatures down to 110 K and high pressure of up to 450 kPa.

The example of the Twin Sting Rig test assembly is taken to describe in detail the efforts to establish a high quality testing tool for ETW and to perform the measurements at dynamic pressure up to 130 kPa. This paper presents an overview of the equipment used, the methods of operation and the practical experience obtained with the devices.

The status and improvements of further tools and test techniques, like the “on-board” miniature video camera for flap gap measurements, the model deformation measurement system, pressure sensitive paint, the anti vibration system and the balance conditioning concept are described briefly.

Introduction

The ETW facility is a high Reynolds number transonic wind tunnel with a partially slotted test section of 2.0 m x 2.4 m. It uses nitrogen as the test gas. With the combined effects of low temperatures and moderately high pressure, Reynolds numbers of up to 50 million at cruise conditions for full span models of large transport aircraft are achieved. The operational temperature range is 110 K to 313 K and the pressure range is 125 kPa to 450 kPa. The Mach number range is 0.15 to 1.3.

Since wind tunnel models are supported by various stings in any configuration, it is necessary to improve the measured data by correcting for sting interference effects in each individual case. One possible method used for this subject is the Twin Sting Rig concept.

The ETW Twin Sting Rig (TSR) enables full span models to be tested such that the localized effects of the rear sting support interference can be obtained by measuring the loads and pressures acting on the rear fuselage with and without a dummy rear sting. Two possible methods are used – measurement of the rear fuselage loads with a live model rear fuselage (“standard” method) or with the strain gauge balances in the support booms of the TSR measuring the loads on the complete model (“enhanced” method). A TSR supported model is typically traversed over a range of incidence from –4° to +10°. This range can be increased up to +18° if the model is tested in inverted position.

Figure 1 presents a typical test assembly for the high Reynolds number testing of a transport aircraft type.

Figure 1: Model Installed on the ETW Twin Sting Rig

The main equipment used for these measurements are a set of strain gauge balances inside the two TSR support booms, a strain gauge balance inside the model fuselage, model inclinometers in front and rear fuselage, dedicated pressure measurements at defined locations and a remotely driven dummy sting. All of this equipment has been used in the complete temperature and pressure range

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of the wind tunnel up to Mach numbers of 0.96.

The experience gained so far with this equipment during several test campaigns will be described hereafter. The aerodynamic results achieved with the system in one of the first campaigns were presented already in 2002 (Reference 1).

Further equipment recently used in ETW is an “on-board” miniature camera used at low speed testing for flap gap measurements of a high lift half model configuration. This camera unit was operating in the complete temperature range down to 115 K, with total pressure up to 355 kPa in low speed testing with Mach numbers of 0.18 to 0.24.

Other techniques are briefly touched. The anti-vibration technique has been further improved and a completely new system is in preparation for the next generation of the system. The development status of further tools and techniques, like model deformation measurement, pressure sensitive paint, and balance conditioning is described.

Overall Description of the Twin Sting Rig

The basic concept of the Twin Sting Rig to establish detailed sting corrections is achieved by measuring the loads acting at the model assembly with and without a dummy sting attached to the sting boss adapter housing. This model load measurement can be performed with two different concepts: the “standard” method with a split rear fuselage load measurement and the “enhanced” method with strain gauge balances inside the booms measuring loads on the complete model.

The typical Twin Sting Rig test assembly consists of the following main components used in both concepts:

- Yoke plate and sting boss adapter
- Two booms with adjustable width fixation
- Wing pylon adapter
- Dummy sting support and drive mechanism

Figure 2 presents the overall design of the rig and figure 3 shows the components involved.

The complete rig was built from the ETW stock material G90C, which is comparable to Maraging 200. The material was chosen to cover the high load requirements, but also to avoid thermal effect in the model structure, since the standard models for ETW are also built from this material. After cool-down and some conditioning period temperature equilibrium is reached and due to the same contraction coefficients any additional thermal stresses are avoided in the wing attachment structure of the model.

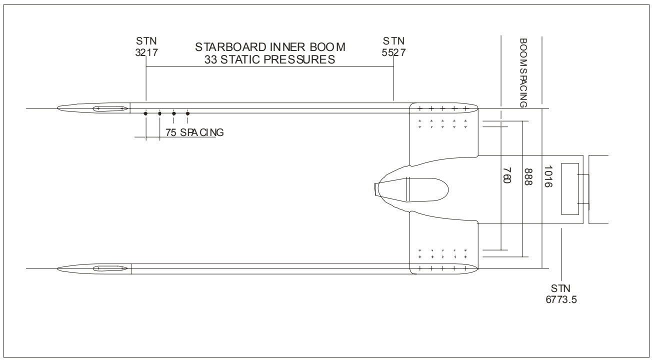

Figure 2: Design Details of the Twin Sting Rig

The yoke plate offers three different spacing for the two booms – 760, 888 and 1016 mm. The booms are 2.9 m long and provide the balance flange interface at the front end. The cross section area has been reduced to minimize the torsional stiffness, which again releases additional stresses to the wing attachment of the pylon. The inner surface of the booms is equipped with 33 pressure holes for static pressure measurement. The wing pylon adapter is part of the model structure and depending on the load envelope it is necessary to integrate the pylon into the wing structure.

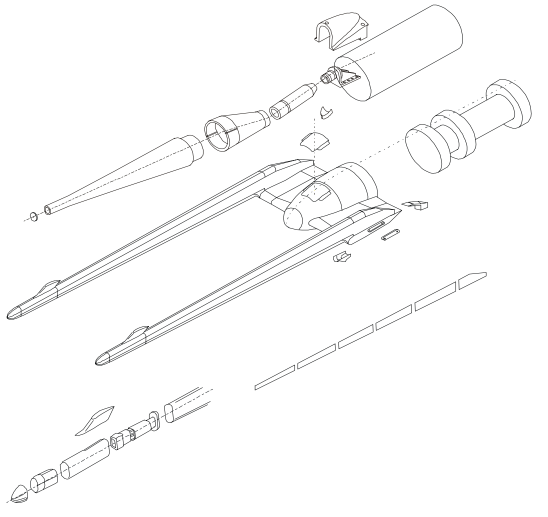

Figure 3: Components of the Twin Sting Rig

Attached to the main structure of the sting boss adapter is the dummy sting support and its drive mechanism. This dummy sting is adjustable by a remotely controlled drive system to compensate the movement due to deflection of the rear fuselage part of the model during incidence change.

These are the commonly used components of the Twin Sting Rig. The two basic versions of model load measurement with the “standard” and the “enhanced” methods includes different components described hereafter. Both methods are shown schematically in figures 4 and 5.

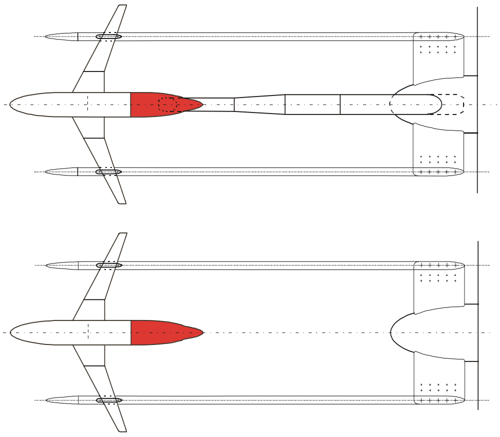

Figure 4: “Standard” Method with Split Fuselage

The “standard” method was used so far for sting interference measurements mainly but also to establish data sets from model configurations with different horizontal tail settings. The additional components used for this test assembly are the following:

- Two boom flexures (3-component balance) for roughly estimating of overall model loads.
- One strain gauge balance (6-component) for accurate measurement of rear fuselage loads.
- Fuselage split plane.

The fuselage of the model is separated into the main front part, with model nose and centre section with attached wing, and the rear fuselage part with horizontal tail plane and fin attached. Both parts are connected to a 6-component strain gauge balance with the non-metric end fixed to the model front part. The loads acting on the rear fuselage part are measured accurately. They are used with high precision data for analyzing the sting corrections and to establish also the performance of the horizontal tail plane settings. The fuselage split has to be monitored very carefully, which involves a detailed knowledge of the internal pressure field and also the development of an external fuselage step during extreme loading by horizontal tail planes.

Since the critical measurement in this test assembly is for the rear fuselage loading the “standard” method was used with simple 3-component flexures attached to the front end of the booms as the interface to the model wing attachment. The measurement of normal force and pitching moment with limited accuracy was used during the test run for observing online that the model loads were kept inside the flexure and model load rhombus.

The incidence of the model fuselage is measured accurately with an inclinometer box installed inside the model front fuselage at the wing adapter joint. Especially for horizontal tail plane measurements with significant deflections at the rear fuselage one additional inclinometer box is attached inside the rear fuselage. This unit is removed when the dummy sting is installed.

The “enhanced” method uses the following additional components:

- Two strain gauge balances (6-component) attached to the front end of the TSR booms measuring the loads of the complete model.
- The incidence of the boom balances is measured with one inclinometer unit attached to the front of each boom balance.

The balance for rear fuselage load measurements is removed and the fuselage is assembled in one piece, avoiding the split opening.

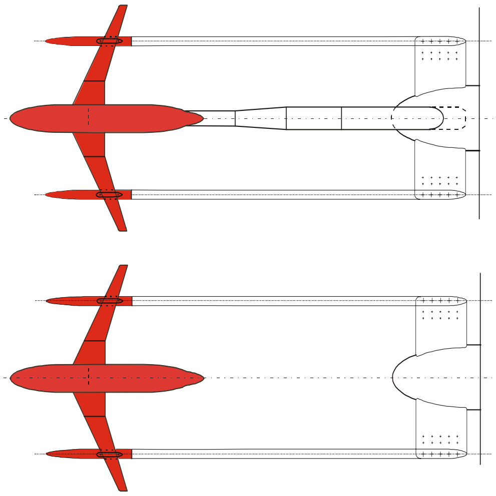

Figure 5: “Enhanced” Method with Boom Balances

Strain Gauge Balances

The different strain gauge balances used are listed below:

- two simple boom flexures with low accuracy measurement of 3-components attached to the TSR booms measuring the complete model.
- two 6-component boom balances measuring loads of the complete model in the “enhanced” method.
- One rear fuselage 6-component balance measuring the loads on the rear fuselage in the “standard” method

The table below presents the three different balances and their load ranges:

		Boom Flexures	Split Fuselage Balance	Boom Balances
Axial Force	N	---	500	1100
Side Force	N	---	2500	13000
Normal Force	N	12000	6000	13000
Rolling Moment	Nm	375	500	450
Pitching Moment	Nm	1250	1600	1300
Yawing Moment	Nm	---	1200	1300

All balances are of maraging steel.

They are equipped with up to 10 Pt100 temperature sensors, which are used to observe the balance temperature during the final temperature conditioning. The standard measurement with the split fuselage balance is performed when all balance temperatures are stable within 1 K.

The boom flexures provide only low accuracy measuring capability for three components, which is sufficient to monitor the normal force, pitching moments and rolling moments of the model during the test run. The online monitoring of these loads is used when approaching the borders of the stress envelope defined for each test assembly.

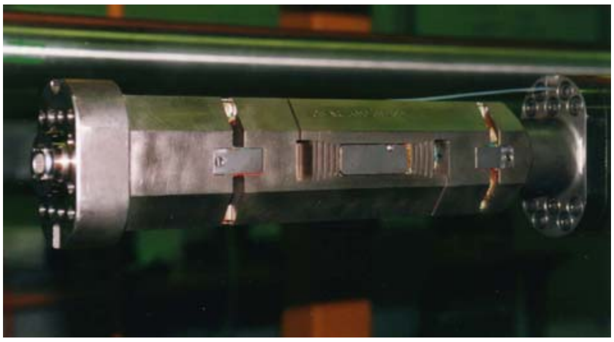

Figure 6: TSR Boom Balance

The two 6-component balances for the TSR boom installation provide an accuracy of 0.1% full scale. The boom balance flanges are adjusted to the boom design and are attached with 10 Inconel bolts each, to the boom structure and at the front end to the wing pylon adapter. The balances are calibrated for the complete temperature range within steps of 25 K covering the full load ranges of the balances. Figure 6 shows the boom balance installed at the TSR boom.

The rear fuselage balance shown in figure 7 is a 6-component strain gauge balance with flanges of 71mm diameter and 350 mm length. The load range is adapted to the high moments occurring during measurements with horizontal tail planes.

The balance structure includes 6 pressure tubes installed close to the neutral centerline to bridge the balance enabling pressures to be measured at the sting cavity with minimal interference.

Figure 7: Split Fuselage Balance

Angle of Incidence Measurement

In the test assembly three different inclinometer positions are in use – in both methods “standard” and “enhanced”, one inclinometer is installed inside the front fuselage of the model. In the “standard” method a second inclinometer is incorporated in the rear fuselage. In the “enhanced” method two inclinometer units are attached to the front of each boom balance.

All units consists of a thermally controlled housings, each equipped with a single-axis Sundstrand Q-Flex and with an Entran three axis miniature accelerometer.

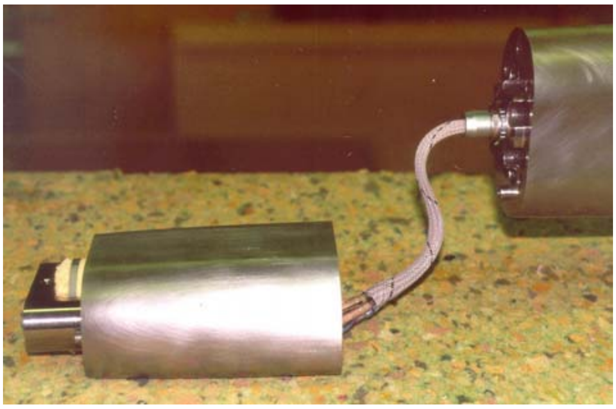

Figure 8: Boom Balance Inclinometer Housing

The boom balance inclinometer is designed with a small housing of 50 mm diameter specially adapted to the boom structure (figure 8).

All inclinometer packages have to be checked after installation according to misalignment and electrical offset. This is done with high precision bubbles attached to the model and boom reference areas and adjusting the relevant area to absolute zero position using the pitching device of the model support. The rear fuselage inclinometer is used in addition to calibrate the fuselage step appearing during horizontal tail plane measurements. Since the horizontal tail plane creates significant loads the fuselage deflects at the split opening. This deflection is calibrated prior to the test by dead weight loading in order to measure also the step occurring at the fuselage. Aerodynamic data correction can be applied for the growing of such a step during the load increase of a test run. Figure 9 shows the installed rear fuselage inclinometer and a typical fuselage split deflection.

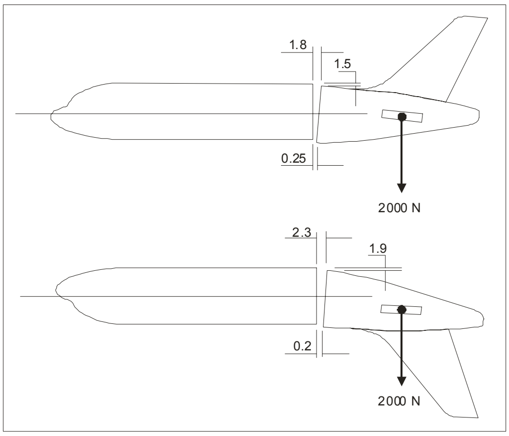

Figure 9: Rear Fuselage Deflection and Inclinometer

Pressure Measurements

Accurate pressure measurement has to be performed in several locations of the test assembly of the TSR. To establish high quality sting corrections the accurate pressure measurement inside the sting cavity is essential when the dummy sting is installed. This is done through the model side with 4 pressures measured on top, bottom and the two sides of the sting cavity. The dummy sting itself is also equipped with 13 pressure holes at the front surface of the sting. Figure 10 present the set-up of pressure measurements in this region.

Due to different positions of the dummy sting inside the cavity the pressure field is influenced. For correction of this effect it is necessary to calibrate the sting position effect on pressures prior to the start of the test run. This is done at the required test conditions by moving the sting into both end positions, which means the touching of the model fuselage. The established correction is incorporated into the final data set.

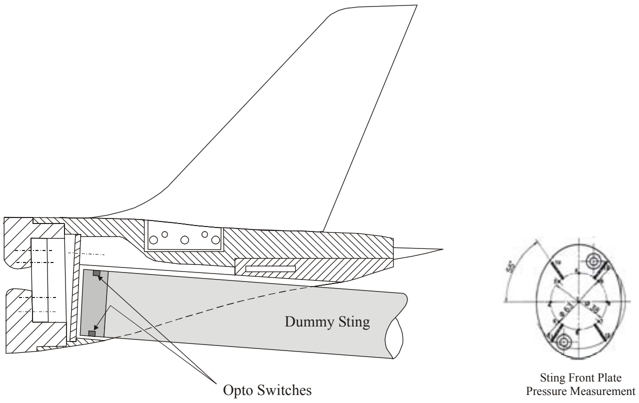

Figure 10: Pressure Measurement at the Sting Cavity

This has to be done for both methods, the “standard” and the “enhanced” method. The order of magnitude for this correction is up to 40 N for a high Reynolds number test case.

Also in both methods it is necessary to measure the pressure inside the boom balance cavities. Corrections applied here are covering the pressure effects on the boom balances directly. Depending on test conditions the correction applied could be in the order of 35 N.

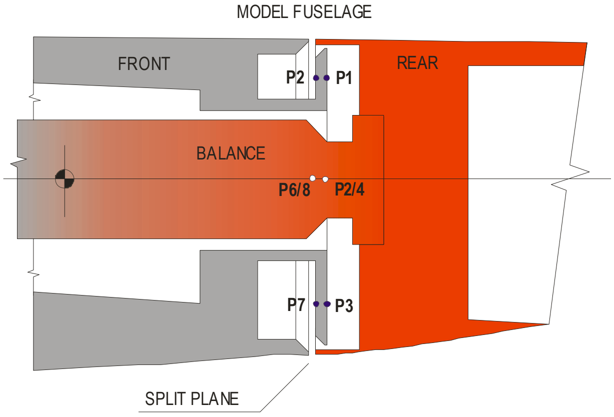

Figure 11: Pressure Measurement at Fuselage Split

The “standard” method required special pressure measurements at the fuselage split. This is performed with a specially developed pressure measurement technique, which involves eight pressure holes only. This has been achieved only by increasing the volume on the metric site of the balance joint. The pressure distributes equally in this cavity as confirmed during all test campaigns performed with this method. Measuring the pressure on metric and earth side give a good information on the forces induced by internal model pressure. The axial loads acting on the live side of the balance are in the order of 140 N for typical high Reynolds number test cases.

Figure 11 gives a sketch of a typical model pressure measurement at the split fuselage.

All of the corrections are applied online in order to have the final data immediately for analysis of aerodynamic effects on the model itself.

Remotely Controlled Dummy Sting

To achieve the highest data quality it is necessary to keep the dummy sting position inside the model as stable as possible. However, by testing at dynamic pressures of up to 135 kPa the dynamic behavior of the dummy sting is of significant importance. In all test conditions, up to Mach 0.96 it must be guaranteed that the dummy sting is stable enough to ensure that it never touches the model fuselage.

The dummy sting itself is an Aluminum structure, representing the near field outer contour of the real single sting. In the single sting test assembly different support methods are used. Attachment angles between 0° and 5° are used with the single sting models and on the TSR the dummy sting has to be in the same corresponding position. Figure 12 presents the different configurations of the dummy sting used so far.

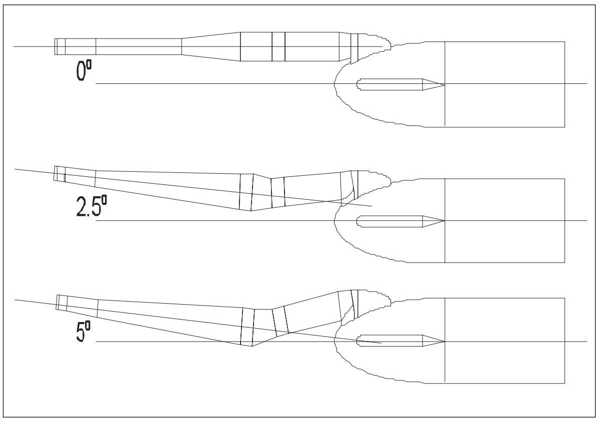

Figure 12: Dummy Sting Configurations

Attached to the sting boss adapter housing the drive mechanism of the dummy sting is incorporated into a special housing , which is insulated and heated for all drive elements. The 11 Watt d.c. drive motor activates through a preloaded cylindrical spindle nut and lever arms the support flange of the dummy sting, which enables the dummy sting to be moved over a range of ±3° in the model incidence plane. The motor is attached by thin blades to the support flange of the dummy sting in order to reduce the thermal conduction from the cold environment to the motor structure itself. Figure 13 shows the arrangement for a 5° sting support.

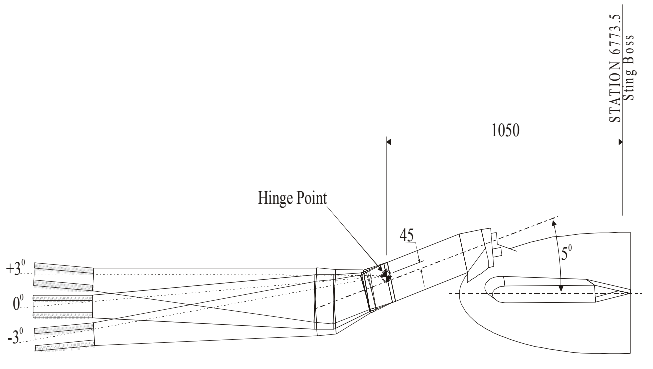

Figure 13: Dummy Sting Positioning

The remote operation is achieved by miniature reflective opto switches installed inside the dummy sting front plate at the upper and lower surface. These sensors are sensitive to distance change. By using two sensors at the top and the bottom contour of the sting the change of the internal fuselage surface due to model deflection is immediately adjusted with the drive unit. The dummy sting position is therefore kept in the center of the sting cavity opening. Figure 10 gives an indication of the position of the opto switches.

Experience Gained During Operation of TSR

This unique test assembly for high Reynolds number testing has been used now in several test campaigns. With its highly stressed complex structures and its dedicated instrumentation the system was used mainly in the flight Reynolds number region above $40x10^6$ at temperatures as low as 115 K and dynamic pressures up to 135 kPa. The Mach number of 0.96 was achieved with dummy sting in position. In several occasions limits in the requested test envelope were experienced due to different reasons, which is reported hereafter in some examples.

In the first test campaigns with test conditions of high dynamic pressure at flight Reynolds numbers dynamic problems occurred with the attached dummy sting. Test runs were stopped due to severe vibration of the dummy sting, since its touching of the model rear fuselage prevented an accurate force and moment measurement. Several trials with different concepts were performed – changing the mass of the sting, incorporated internal damping devices, stiffening the internal support system and wire damping by external attachment were used. One source of vibration could be identified easily from the obvious flow separation at the fuselage/sting opening. To verify this phenomena and find a possible solution to avoid such effects investigations with Kulite measurements in this area were performed. Figure 14 gives an indication on the dynamics involved in the test assembly.

Figure 14: Vibration of the Dummy Sting

This critical test campaign was finished with an ad-hoc solution of damping wires attached to the dummy sting. Increasing the stiffness of the drive support also reduced the level of the vibration. However, the thickened support elements increased the thermal conduction, which stopped the functioning of the motor in the cold part of the test run at high Mach numbers due to reduced temperatures inside the housing. Lowering the Mach number to 0.2 was sufficient to increase the temperature inside the housing, since the thermal conduction was low enough. After interruption of the test run for heating exercises all test points were taken.

After this first test experience it was decided to change the Eigenfrequency of the system in general. The internal support was redesigned completely. The new drive unit is currently under manufacture.

Another challenging item is the design of the model attachment to the TSR booms. Due to interference aspects the fixation of the model should be as far outboard as possible. However, the high dynamic pressure involved requires a stiff wing structure and a sufficient pylon thickness to accommodate the combination of normal force (up to 20000 N) and high bending moments (up to 80Nm) at the clamping bolts. Divergence problems appear if the wing structure is too weak, and could therefore limit the test envelope significantly. Experience with severe divergence limitations was gained in one test campaign with values of divergence factors down to 1.7. The standard limit is 3. Due to the well known model behavior, detailed calculations, step by step increase of model incidence and online monitoring of divergence development with alpha, it was possible to achieve the requested test conditions in this special case.

The loads transmitted to this most critical joint are normally the limiting item during the test run. Online monitoring of the model loads, especially normal force, pitching moment and rolling moment is essential and the individual test runs are often driven up to the structural limits of the test assembly. However, for correct determination of the structural limits it is essential to identify exactly the forces and moments acting in this area. ETW has established during several design approval procedures detailed knowledge on this item in order to give sufficient advise during early design phases for future models.

The accurate incidence measurement of the model itself, its rear fuselage part and the boom balances requires a very detailed calibration of electrical offsets and misalignment prior to the test run as described before. Changing the model dead weight during configuration changes requires an internal balancing of the model weight to avoid changes of the centre of gravity. Such a change influences the model twist of the attached wings and therefore the zero positioning. The removal of the dummy sting for example requires to fill the fuselage hole with a covering insert. Such an insert could easily weigh 50 N. Taking into account the long lever arm the wing twist will certainly be influenced. To adjust this weight change a mass inside the model front fuselage is modified accordingly.

This mass inside the front fuselage can also be used to change the Eigenfrequency of the test assembly. By movement of the centre of gravity towards the model nose, the mass distribution is changed and the dynamic behavior of the test assembly can become more stable in the pitch torsion frequencies. Since the wing is a comparatively soft spring the presence of broad band excitation, caused by flow separation at areas like the fuselage/sting intersection, could lead to model oscillations. Testing at high dynamic pressure the planned measurement could be limited significantly due to extreme values of model acceleration. Especially the configurations without horizontal tail planes attached are sensitive to these phenomena. The cavity in the front fuselage normally allows to attach some extra weight. Using a fusible alloy, Cerrobend, in the liquid phase by heating it to 330 K the front fuselage cavity can be filled. Up to 350 N were achieved in one project.

All the experience gained with high dynamic pressure measurement at cryogenic conditions is increasing the knowledge on such complex test assemblies.

Other Tools and Techniques

The cryogenic test conditions in ETW require a continuous development of new test techniques specially adjusted to this low temperature region. Items like wing and flap deformation measurement, flow visualization by laser techniques, temperature and pressure sensitive paint, infrared techniques, balance conditioning systems, anti

vibration concepts are under development.
One example is the flap gap deformation measurement for a high lift configuration of a half model.

In low speed high lift configurations of half model test assemblies the thin structures of wing flaps raises the concern on aerodynamic influences of deformation effects. It is therefore essential to get some knowledge on the magnitude of the existing deformation and compare it with CAD information. A half model was equipped at ETW with a miniature CCD camera for online observation of flap gap deformation. The camera was installed inside the fuselage and the viewing angle was adjusted through a 10 mm penetration onto the wing trailing edge.

Figure 15: Miniature CCD Camera and Equipment

Figure 15 shows the camera equipment. A heated housing and insulation are used to thermally control the electronic part of the camera unit. The lens was used in the complete temperature and pressure range without any further protection. The view angle and the focus was adjusted to the outboard flaps as presented in figure 16. Since the camera was not remotely controlled all adjustments had to be done prior to the test run. Figure 17 shows the typical result achieved from the online monitoring. The accuracy of the measurement is strongly depending on the quality of the selected camera. In this case a high quality miniature CCD camera was selected to gain first experience with such systems in cryogenic environment. The images provide a Pixel resolution of 0.2 mm when transferred to the model structure. To increase the contrast at the trailing edges of the wing the edge was painted with fluorescent marker. By using additional UV light the contour of the wing was well monitored.

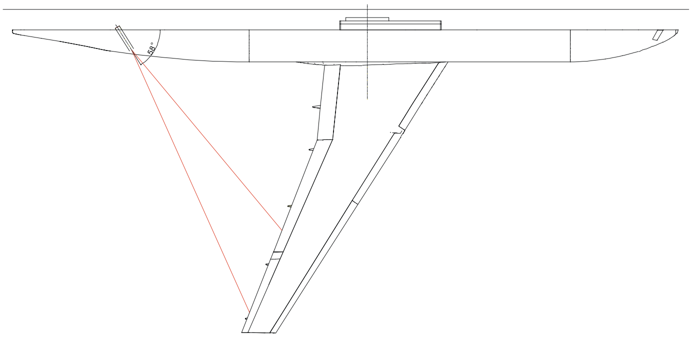

Figure 16: View Angle of Installed Camera

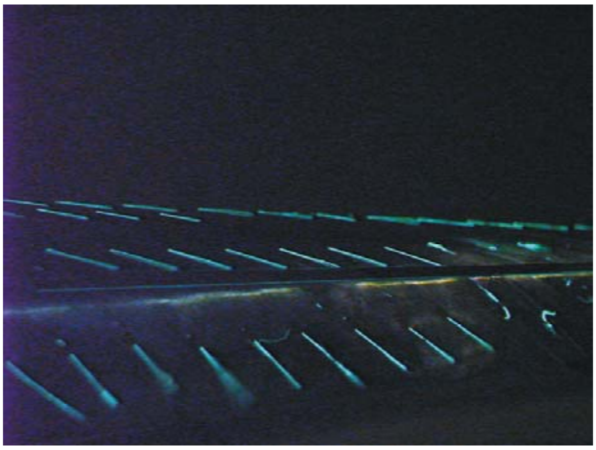

Figure 17: Typical Image

The status of the other tools and techniques currently under development is summarized below:

Pressure Sensitive Paint (PSP)
In ETW the pressure distribution on aircraft models is assessed by the use of pressure plotted wings and fuselage pressures. Beside the related high manufacturing cost, the resulting load limits of the model itself may be remarkably reduced due to the weakening of the wing structure caused by the required machining to house pressure tubes. To overcome such problems in the near future, first steps have been made by a co-operation with national research establishments to develop a Pressure Sensitive Paint (PSP) System at ETW. The qualified paint for cryogenic environment exists, although further improvement is still considered, and the adaptation of the illumination system and processing software is under development. A system checkout under realistic high speed and high Reynolds number conditions is scheduled for early 2003. Replacing PSP for this test campaign by a cryogenic Temperature Sensitive Paint (which requires no oxygen), the illumination system including the paint will be validated by comparing the result with the images of the available cryogenic Infrared Camera, which will be used in parallel.

Wing Deformation - MDMS

Although the system is operational since several years problems in data evaluation so far prevented a fully automatic use of the system. Further improvements were performed and the system has been used again in the complete range of test conditions. The data achieved this time are very promising. The comparison of deformation data provided by the client and data from the ETW deformation analysis by wing pressures (Reference 2) are in good agreement as shown in figure 18. Figure 19 presents further comparisons at different lift coefficients. Further improvement to establish an online information during the test run is necessary.

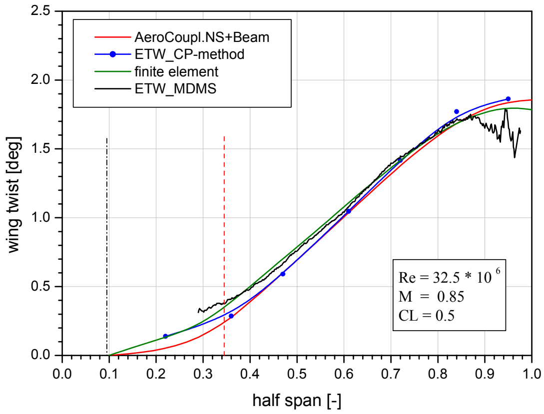

Figure 18: Comparison of Different Methods

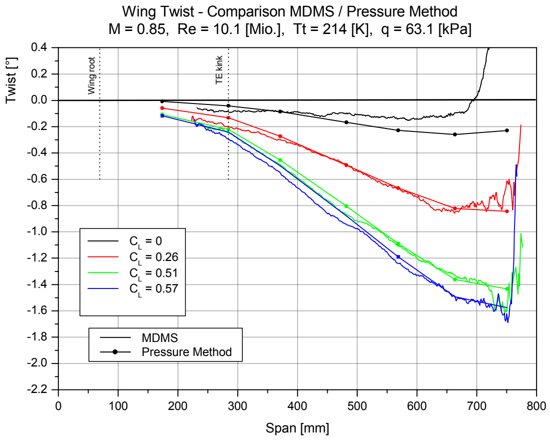

Figure 19: Comparison of Deformation Data at Different Lift

Quantitative Flow Measurement by Doppler Global Velocimetry (DGV)

Driven by the presence of thin boundary layers on the wing when testing at high Reynolds numbers, any optical system for quantitative measurements of flow field components is highly appreciated. Following comprehensive investigations to provide a suitable seeding material at cryogenic tunnel conditions, a laser light sheet based system has been designed and successfully tested in the lab.

Tunnel installation is scheduled for mid 2003 to assess the three velocity components of the wing tip vortex to be found at a plane downstream of a half model.

Anti Vibration System

The current system is used successfully as standard equipment for all full model test assemblies (Reference 3). A new concept with further significantly improved performance is in preparation and the first assembly of the system is planned for spring 2003. This system should enable model vibrations, especially in the pitch mode, to be further reduced. Using this method the critical section of balance sting joint is free again since the system will be placed back in the non-critical sting structure.

Active Balance Conditioning

The system for full model balance conditioning has been improved and is used as a standard tool during all test campaigns. The semi-automatic systems allows the model conditioning to be completed with the tunnel conditioning. A typical cool-down from 300 K to 115 K takes with the system active about 3 hours with the system actuated. The balance does not see gradients above 5 K during the whole temperature cycle and is after cool-down conditioned within half an hour to the test temperature within 1 K.

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