AIAA-2002-0423

First Measurements on an Airbus High Lift Configuration at ETW up to Flight Reynolds Number

Juergen Quest* & Martin C. Wright**
ETW GmbH, Ernst Mach Strasse, D-51147 Köln, Germany
jq@etw.de, mcw@etw.de

Heinz Hansen+
AIRBUS Deutschland GmbH, D- 28183 Bremen, Germany
h.hansen@airbus.dasa.de

Gabriel G. Mesuro++
EADS – CASA, John Lennon S/N,28906 Getafe, Spain
gabriel.garcia.mesuro@casa.eads.net

ABSTRACT

The capability of the European Transonic Windtunnel ETW to test simultaneously at cryogenic temperatures down to 110 K and at pressure levels ranging from 100 kPa up to 450 kPa allows to perform separated experimental investigations of pure Reynolds number and aeroelastic effects. This capability combined with the recently established half model test system has been used to carry out the first test campaign with a high lift configuration in the low Mach number range. Experimental investigations and analytical work was performed as task of the European research project EUROLIFT which forms part of a "European High Lift Programme". The present paper provides information about the background of the test campaign and specific model features. Typical findings on the "clean wing" as well as for a "landing" configuration are described with special emphasis on Reynolds number effects. The benefit of a capability to operate from minimum up to flight Reynolds number is documented with reference to scaling effects. To validate ETW for testing high lift configurations at low speeds, gained results have been referenced to data recorded in the Airbus LSWT facility and the German - Dutch windtunnel KKK. Also flight data could be made available for quality comparison.

INTRODUCTION

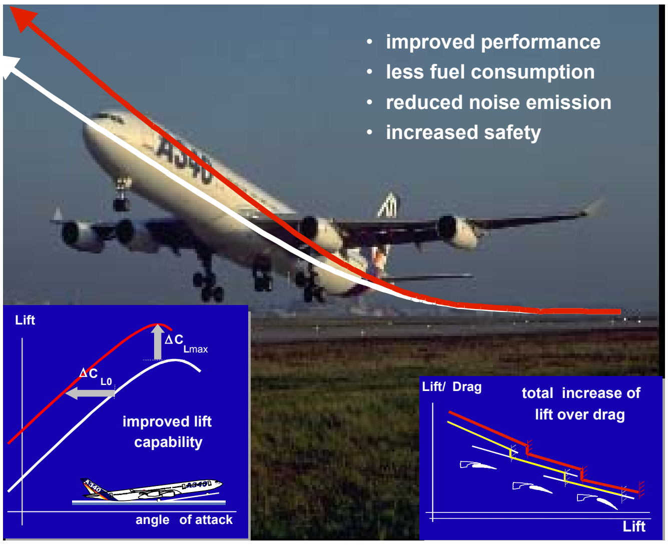


Figure 1 : Potential for improvement of new high lift Systems

The current competing market of civil transport aircraft asks for products with the best possible advantage for the customer. Within this scope of permanent pressure for the aircraft industry to improve their products concerning costs, performances, reliability and emissions the development and production of high-efficient new high lift systems for new or modified aircraft will play an important role in the future as outlined in figure 1. An increased understanding of the flow physics of high lift systems and the ability to optimise these systems in terms of more efficient, yet simpler designs in combination with a high accuracy of flight performance prediction in an early stage of

---

* *Chief Aerodynamicist at ETW GmbH, AIAA member*
** *Senior Test Engineer at ETW GmbH*
\+ *High Lift Specialist at AIRBUS-Germany*
\++ *Head of flight physics at EADS-CASA*

development will provide a strong contribution to the competitiveness of aircraft manufacturers.

Most of the high lift testing to date has been done at sub-scale conditions. Field performance and handling qualities for the aircraft are then derived by extrapolation. Many of these scaling effects strongly depend on the Reynolds number as the characteristic parameter between subscale and flight conditions and may change for different aircraft designs as demonstrated in figure 2. These scale effects can introduce an element of risk to any aircraft programme. Costly design modifications or performance shortcomings in the aircraft certification phase may occur during flight tests. The ability to understand high lift aerodynamics in detail and to predict flight conditions precisely is therefore considered as mandatory for a successful economic and efficient aircraft design.

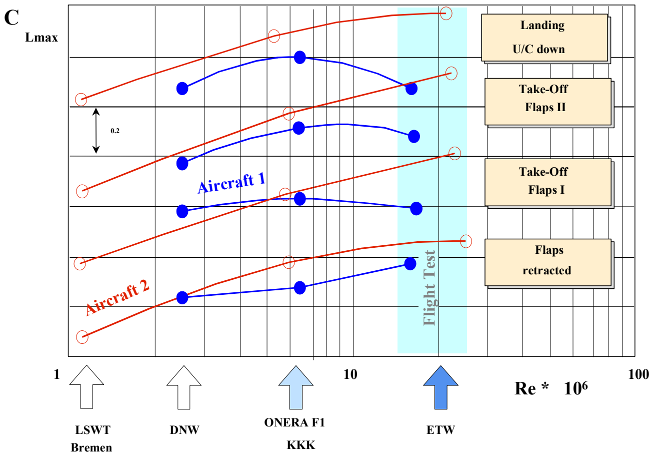


Figure 2 : Typical Reynolds number effects on CL $_{\text{max}}$

The flow field of a high lift configuration is extremely complex: Strong interactions of the boundary layer state (laminar, turbulent, re-laminarised, separated, re-attached ?) and the wake development behind each high lift element (slat, main wing and flap) may exist. All these effects are strongly dependent on Reynolds number due to the change of the boundary transition and stability. Different types of transition may be found: Attachment line transition, transition by cross flow instabilities or by Tollmien-Schlichting waves. Most of these transition mechanism act close to the leading edge. Near to maximum lift re-laminarisation may eventually occur due to the strong acceleration around the leading edge of the high lift elements, and additionally increase the complexity of the flow. Interferences of transonic flows at high angles of attack and rising Mach numbers combined with local flow disturbances introduced by three dimensional effects (e.g. nacelle and pylon etc.) will still avoid in the near future a sufficiently accurate (in the above sense) prediction of the low speed performance by computational tools or by measurements in low Reynolds number wind tunnels.

Using the unique capacity of testing aircraft models up to flight Re numbers in the cryogenic pressurised European Transonic Windtunnel ETW combined with the capabilities of the new half model testing technique, the existing gap between sub-scale testing and flight conditions will be closed. The European research programme EUROLIFT offers for the first time to perform 3D low speed high lift measurements up to flight Re numbers in a wind tunnel. The main objectives for this first low speed wind tunnel entry within EUROLIFT can be summarised as :

- ❑ Validation and exploitation of ETW as a commercial high quality tunnel for low speed high lift testing linking low Reynolds number capabilities to flight conditions
- ❑ measurements of Re effects up to flight Re numbers for realistic aircraft configurations concerning the lift, drag and stall behaviour
- ❑ comparison of ETW with other low-speed test facilities
- ❑ comparison of ETW results with flight test results

FACILITY AND MODEL SET-UP

For the validation procedure an existing Airbus-Germany owned typical Airbus model has been made available as a sample of a modern transport aircraft. This model has been extensively tested in the LSWT in Bremen and in the cryogenic tunnel in Cologne (KKK). Based on the gained information, results from ETW can be cross-checked in the appropriate Ma/Re limits at ambient and cryogenic conditions.

The model used in ETW during the period from 17-21 July 2000 wa an 1/13.6 scale half span model of an typical Airbus aircraft. It was designed and manufactured by Airbus-Germany for operation in cryogenic environment. This model was the first low speed model world wide which can be used in pressurised cryogenic tunnels such as ETW. Due to the specific design, measurements over the complete speed range from low Mach numbers up to cruise conditions and up to flight Reynolds numbers can be performed.

Pre-assembled flap sets

Individual slat sets for each configuration

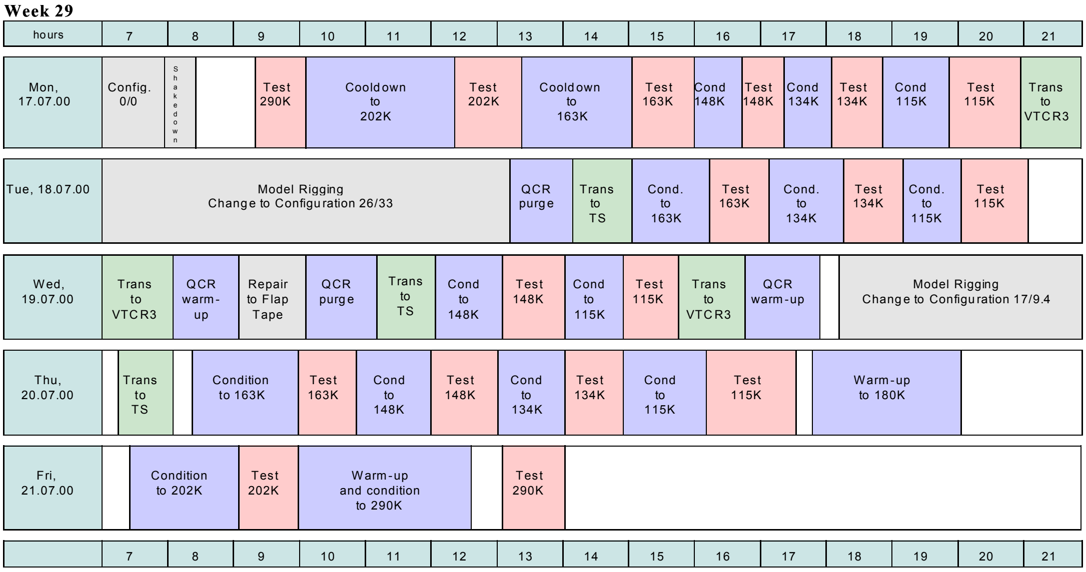
Figure 3 : Model components for high lift testing

A broad range of different take-off and landing configurations exist for this cryogenic model. For each configuration a complete set of slat and flap devices are available as can be seen in figure 3 and can be pre-assembled. This provides an easy configuration change and enables a remarkable reduction for the configuration change time, which is an important issue in expensive cryogenic wind tunnels.

As far as possible all real aircraft details of the Airbus aircraft type are represented by this model: wing root fillet, shroud extension fairing, wing tip device, through flow nacelles, nacelle strake etc..

Except the fuselage no transition fixing was applied. For flow visualisation a very dense distribution of thin (∅ 0.02mm) cryogenic mini tufts has been attached to the upper wing surface. This selected density (higher then in KKK and LSWT) was in agreement with the flow visualisation arrangement during flight tests to allow for direct comparisons.

Unfortunately the settled cost frame of the project did only allow to allocate 4 tunnel days for testing of 3 different configurations. The test programme and the achievements can be summarised as follows : a total of more than 150 productive polars has been performed and the full Reynolds number range could be covered with the clean wing and the landing set-up by testing at six temperatures and corresponding pressure levels. More details can be taken from figure 4 which presents the test scenario. Running the facility from about 7 am up to 9 pm, changes of the model configuration were scheduled during night time to keep the tight time schedule. The figure reveals that due to an unforeseen event the first change shifted already to the next morning hence causing a delay of about half a day.



Week 29

hours | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21

Mon, 17.07.00 | Config. 0/0 | Shakedown | Test 290K | Cooldown to 202K | Test 202K | Cooldown to 163K | Test 163K | Cond 148K | Test 148K | Cond 134K | Test 134K | Cond 115K | Test 115K | Trans to VTCR3

Tue, 18.07.00 | Model Rigging Change to Configuration 26/33 | QCR purge | Trans to TS | Cond. to 163K | Test 163K | Cond. to 134K | Test 134K | Cond. to 115K | Test 115K

Wed, 19.07.00 | Trans to VTCR3 | QCR warm-up | Repair to Flap Tape | QCR purge | Trans to TS | Cond to 148K | Test 148K | Cond to 115K | Test 115K | Trans to VTCR3 | QCR warm-up | Model Rigging Change to Configuration 17/9.4

Thu, 20.07.00 | Trans to TS | Condition to 163K | Test 163K | Cond to 148K | Test 148K | Cond to 134K | Test 134K | Cond to 115K | Test 115K | Warm-up to 180K

Fri, 21.07.00 | Condition to 202K | Test 202K | Warm-up and condition to 290K | Test 290K

7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21

Figure 4 : Test Scenario of the half model entry

It could be proven that the capability of ETW for half model testing allows to cover the full Reynolds number range by variations of pressure and temperature within a single day per configuration.

As already addressed above, the presented test on a high lift configuration in low speed environment was the first commercial entry of this type for ETW. To gain experience and to investigate specific flow behaviour and model responses a more comprehensive matrix of test conditions was agreed with the clients for the clean wing configuration. All polars taken at Mach = 0.2 are indicated in figure 5.

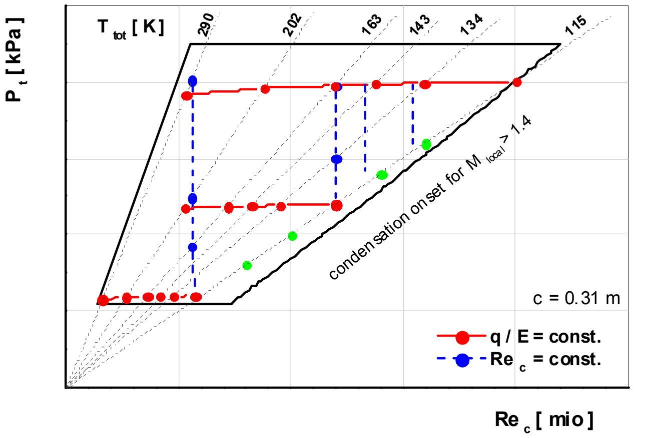


Figure 5 : Test conditions for the clean wing configuration

While the comprehensive tunnel calibration and flow field analysis for 3d-model testing was already performed around the mid 90's, the half model test capability at ETW was established in 1999. As low speed testing is typically undertaken in solid wall facilities and for the sake of a reliable wall interference assessment, it had been decided to calibrate the tunnel in a solid wall as well as in a slotted wall configuration. The latter, mainly devoted to high speed testing, is characterised by opening 3 slots on each side wall which may be closed by inserts to create the solid wall variant. Tunnel buoyancy and Mach number have been determined as part of the optimisation of the bottom wall and re-entry flap setting operating with an empty test section.

Investigations with an empty tunnel covering a Mach number range from 0.15 up to 0.98 with Reynolds numbers up to 70 millions (based on c = 0.31m) have been added to account for the effect of the calibration devices. It was found that when operating with an unchanged wall setting over the full tunnel envelope up to M = 0.98, a small axial gradient equivalent to a Mach number change of 0.002 has to be tolerated. More detailed results are reported in[1].

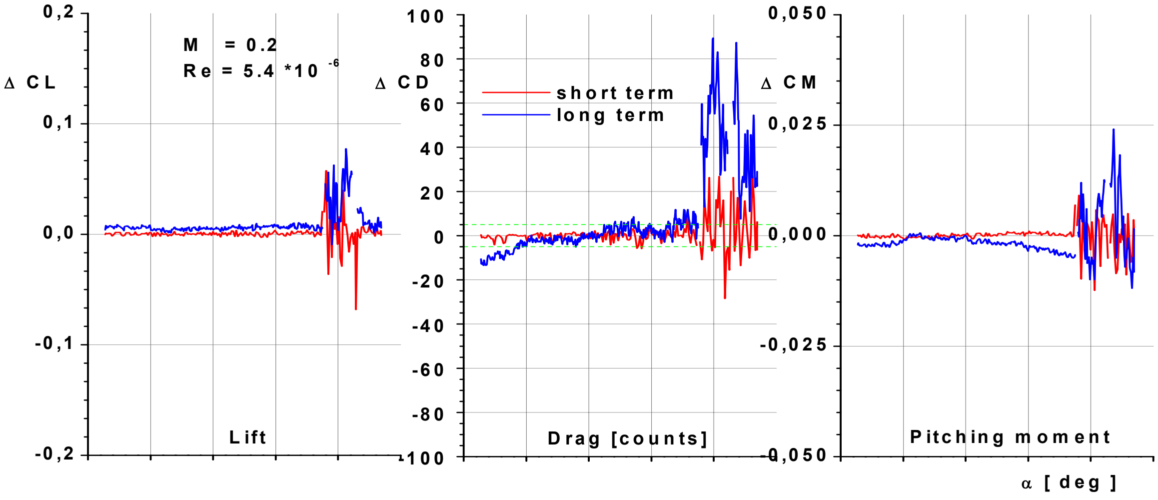


Figure 6 : Short and long term repeatability

Trials to validate quantitatively the complete half model technique could be performed by using the available model. Based on the excellent thermal stability of the temperature conditioned external balance, high levels of medium term repeatability were revealed for forces and moments. About half a year later the same model could be acquired a second time to investigate the long term repeatability and to check the outcome of tuning the instrumentation and data acquisition set-up. Some major findings are given in figure 6, where increments of lift, drag and pitching moment are presented for a low speed case at $Re_c = 5$ million. This Reynolds number is close to the maximum value which can be generated by pressurised facilities open at ambient temperatures or cryogenic ones without a capability for pressure variation. Slightly increased increments found for the long term repeat reflect obvious deviations going along with a complete re-assembly and re-instrumentation of the model. The dashed lines mark the accuracy level of the used balance which is designed for a load range up to 5 kN in axial force but was only operated at low load conditions in the present exercise. Without a consideration of the peaky area representing highly separated and unsteady flow behaviour on the model, a very satisfying repeatability can be assessed.

TESTING THE "CLEAN WING" CONFIGURATION

Although not being considered as a high-lift configuration, a model with a clean wing offers even at low speed conditions a substantial potential to investigate flow development as a function of Mach and Reynolds number. In the framework of the windtunnel entry a comprehensive matrix of test conditions has been experimentally investigated using the advantageous capability of ETW to perform pure Reynolds number or aeroelastic traverses as already emphasised in figure 5. Figure 8 shows the maximum lift behaviour as function of the chord Reynolds number combining the results of testing at different model loads. The Reynolds number ranges from values achieved in an ambient air facility up to flight conditions. A clear trend shows a reduction of maximum lift with increasing Mach number for the lowest speed range. Simultaneously the peak area become less distinct and is shifted towards higher Reynolds numbers. It was concluded that no wing distortion is evident for the selected model configuration.

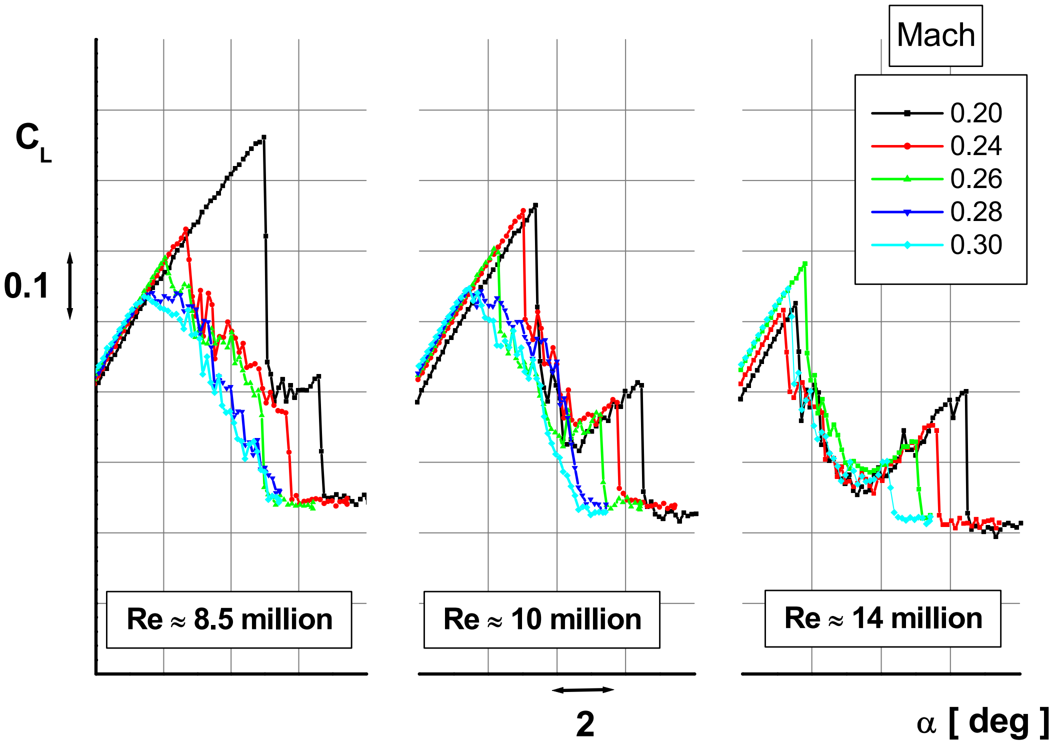


Figure 7 : Lift vs pitch angle for different Reynolds numbers

The individual development of lift when pitching the model can impressively be demonstrated by the samples given in figure 7. For Mach = 0.2 and a Reynolds number corresponding to the lift peak we observe a sudden steep drop in lift caused by an extended flow separation on the wing. Higher Mach numbers are characterised by a more moderate reduction in lift.

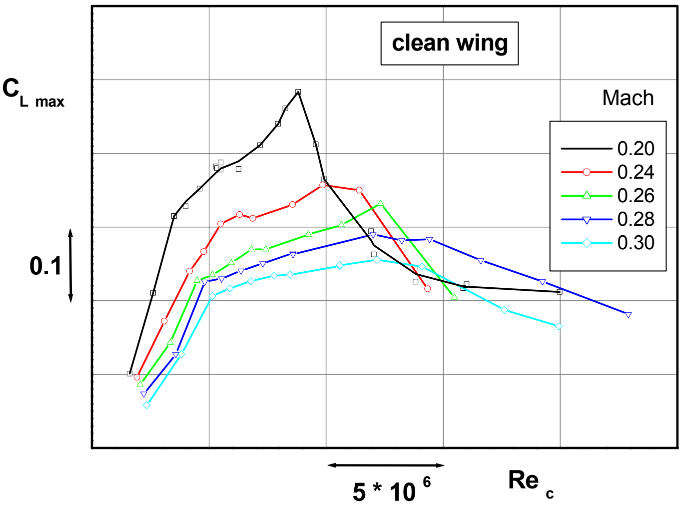


Figure 8 : Maximum lift vs Reynolds number

Increasing the Reynolds number goes along with a change from the “smooth” to the “drop type” behaviour with rising Mach numbers.

A steep reduction in lift following CL_{max} is evident for all investigated Mach numbers when the Reynolds number approaches flight condition. A further increase of model incidence generates a lift recovery which appears to be strongly Mach number dependant. This process will be terminated by a separation onset over the main part of the wing generating a second stepwise reduction in lift.

It is well known that aerodynamic features like re-laminarisation and attachment line transition play an important role in the flow development on wings at such speed conditions. Regrettably the objective of the windtunnel entry did not include further research considerations and hence no specific instrumentation was available or operated to investigate such effects.

While clean wing results at very low Mach numbers are more of theoretical interest, the real aircraft is able to fly in this configurations at Mach around 0.3. A typical set of lift curves over a wide range of Reynolds number reveals a quiet variant lift behaviour. When the flow on the wing is predominantly attached, a Reynolds number increase generates a raise in lift curve slope up to about Re = 10 million. The response of lift on the first appearance of flow separation is strongly Reynolds number dependant. Globally speaking, two different types of lift behaviour could be identified . For very low numbers as well as for Re > 12 million separation is characterised by its sudden onset over a wider area on the wing going along with the first steep drop of CL as to be seen on the figure. At medium Reynolds numbers we notice a smooth reduction in lift when increasing the incidence of the model above a certain value. Here the second drop in lift caused by separations in the outer wing area is missed.

To monitor and to document specific flow behaviour, a matrix of minitufts suitable for cryogenic environment had been pasted on the model surface. Each tuft is individually attached with a thin Kapton – foil to provide sufficient stability at highly unsteady flow conditions. Figure 9 compares the two different flow situations described above. Both images have been taken at identical Mach number and angle of attack of the model. Having flipped one wing by image processing allows an easy comparison of the differences being found. It turns out that the flow is obviously attached over the full chord in the vicinity of the fuselage for a Re-number around 7 million. Reverse flow is only indicated over all small pocket close to the leading edge despite tuft rows number 3 to 7 (seen from the centreline) exhibit an increased level of instability.

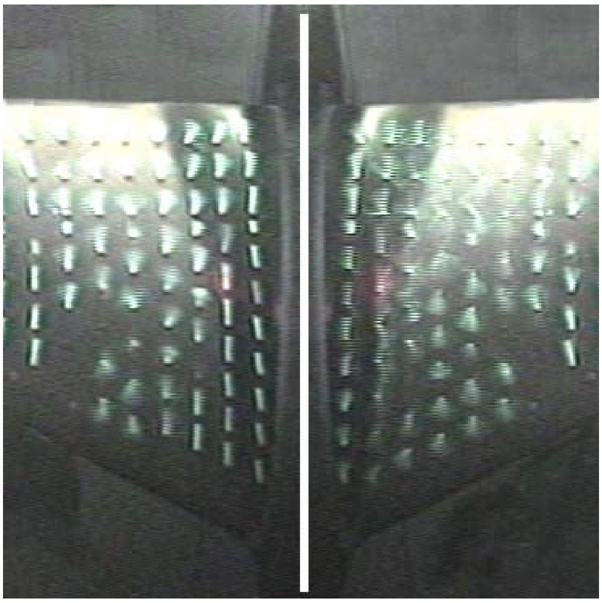


Figure 9 : Reynolds effect on flow separation

At a Reynolds number of about 13 million we observe an extended area of reverse flow ranging from tuft row 2 to 7 over the full chord. This corresponding flow separation is generated by only a small change in model incidence in contrast to the appearance at Re = 7 million. While the origin of the demonstrated development is supposed to be anchored to the flow around the nacelle and pylon, the result reveals the importance and requirement of dedicated investigations at varied Reynolds numbers.

A complementary proof to impressively document the benefit of high Reynolds number testing for aircraft design is provided by figure 10. Here maximum lift is presented versus Re-number at Mach = 0.28 with reference to figure 8. The good match of the incorporated flight data increase the level of confidence in the ETW measurements and confirm the correctness of the measured trend.

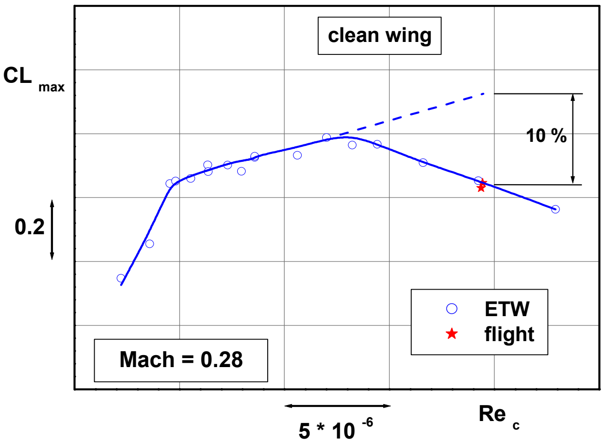


Figure 10 : Maximum lift vs Reynolds number at Mach = 0.28

From testing in pressurised ambient temperature tunnels or cryogenic facilities operating at atmospheric pressure conditions, the trend of CL $_{max}$ up to about 6 millions may be gained. But applying classical scaling rules to extrapolate the maximum lift to flight conditions would introduce an error of more than 10% in lift as shown in the figure. Empirically determined correction factors are often used for an improved assessment but might be restricted to known test configurations and hence bear an unknown level of uncertainty.

Another important parameter for the ability assessment of an aircraft is seen in the ratio of lift over drag versus lift as given in figure 11. It is evident that the ratio is permanently increasing with Reynolds number mainly due to the reduction in friction and consequently in drag. But with respect to the demonstrated behaviour of flow separation also the lift will become subject to Reynolds number effects.

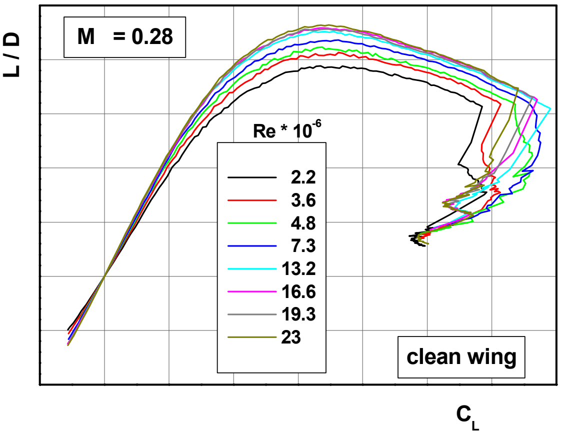


Figure 11 : Lift over drag vs lift

Figure 12 has been extracted from figure 11 to highlight the effect of Reynolds number on the ratio of L / D. Relying on results from a pure ambient air test you would be faced to an about 20% increase in the absolute value when extrapolating to flight conditions. By nature the slope of the curve is steeper in the lower Reynolds number range. When operating at the limits of conventional or un-pressurised cryogenic tunnels a rise in the lift over drag ratio of only 13% can be explored due to the non linear behaviour of the curve which is driven by Reynolds depending lift and drag development.

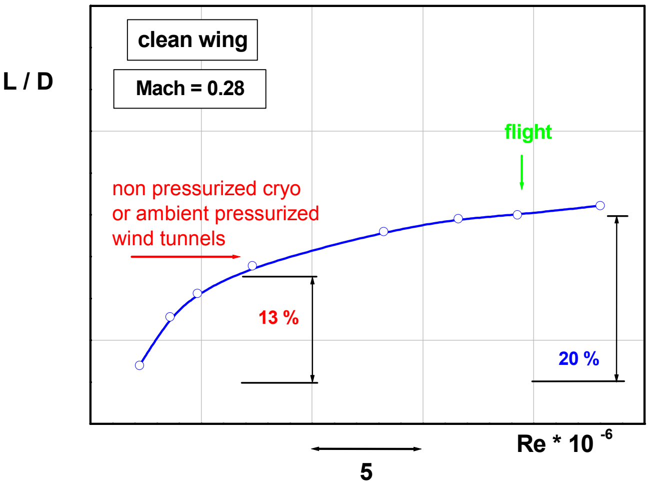


Figure 12 : Lift over drag vs Reynolds number at constant lift

REYNOLDS EFFECTS ON THE "LANDING" CONFIGURATION

While experimental investigations on a clean wing model are highly appreciated from a research point of view to improve understanding of flight physics, the paramount objective of the wind tunnel entry was seen in the acquisition of reliable data for a high-lift model configuration. The individual test series dedicated to take-off and landing configurations have already been outlined in figure 4. Both set-ups are characterised by filigree mechanical components, i.e. extremely thin flaps, tabs or ailerons. Consequently such parts might be more sensitive resulting in a specific responses to variations of pressure load or rapid temperature changes.

Such subjects were addressed by using the full capabilities of ETW to vary the Reynolds number at constant q over E (Youngs modulus). The resulting maximum lift is shown in figure 13. The windtunnel results obtained in ETW have been combined with the findings from testing in the Airbus-Germany low speed facility LSWT located in Bremen, which can only be operated at ambient pressure and temperature and hence generates the lowest Reynolds number. To match this condition ETW was forced to be operated outside of its official envelope as the tunnel pressure has always to be kept above the local atmospheric pressure to avoid any suction of external air. Nevertheless very satisfying agreements could be achieved which will be discussed later in more detail.

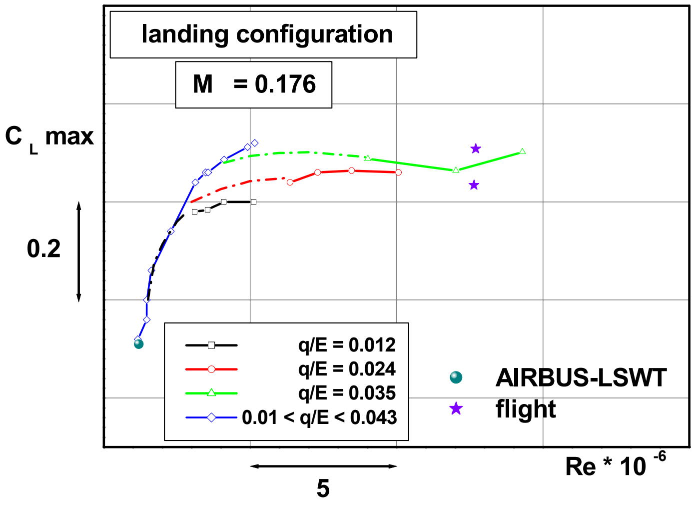


Figure 13 : Maximum lift vs Reynolds number

Obviously the achieved lift levels seem to be affected by aeroelastic effects. Increasing the dynamic head shifted the corresponding maximum lift to higher values. This conclusion has been drawn despite of the fact that the observed differences are only in the order of about 2 lift counts. But a high level of confidence in the reduced data exists with reference to the quoted data quality of the facility (i.e. better than +/- 1 lift count) and with respect to the performed repeat of polars.

The cited trend is also confirmed by results obtained in a second entry performed about one year later using the identical re-assembled model configuration. Being restricted to testing at ambient temperature the Reynolds number was increased in the classical way by raising the tunnel pressure. Ending up with a total head of about 450 kPa the highest values of CL_{max} have been achieved pointing out the eventual existence of a potential for further lift increase by a modified shape or setting of the high lift devices.

Flight data are additionally implemented in figure 13 for the sake of completeness and to impressively demonstrate the test capabilities of ETW also for low speed investigations.

At the beginning of testing, aeroelastic effects were questioned with reference to the conclusions drawn for the clean wing configuration and bias was thought to be the source of the observed mismatch. But careful repeats of polars revealed that flow characteristics and model responses really differ as shown in figure 14.

Here increments in Mach number, lift and drag have been plotted against model incidence for the same Reynolds number generated with minimum and maximum total head available in the tunnel at this speed range. The resulting dynamic head thus varies by a factor of about 4. In the lower sub-figure the Mach number is tared to the nominal value of 0.176. Subsequently each data point is referenced to the first point gained in the relevant polar. At very high incidence deviations in the order of 0.003 have to be stated but the averaged difference between the two polars is only around 0.001.

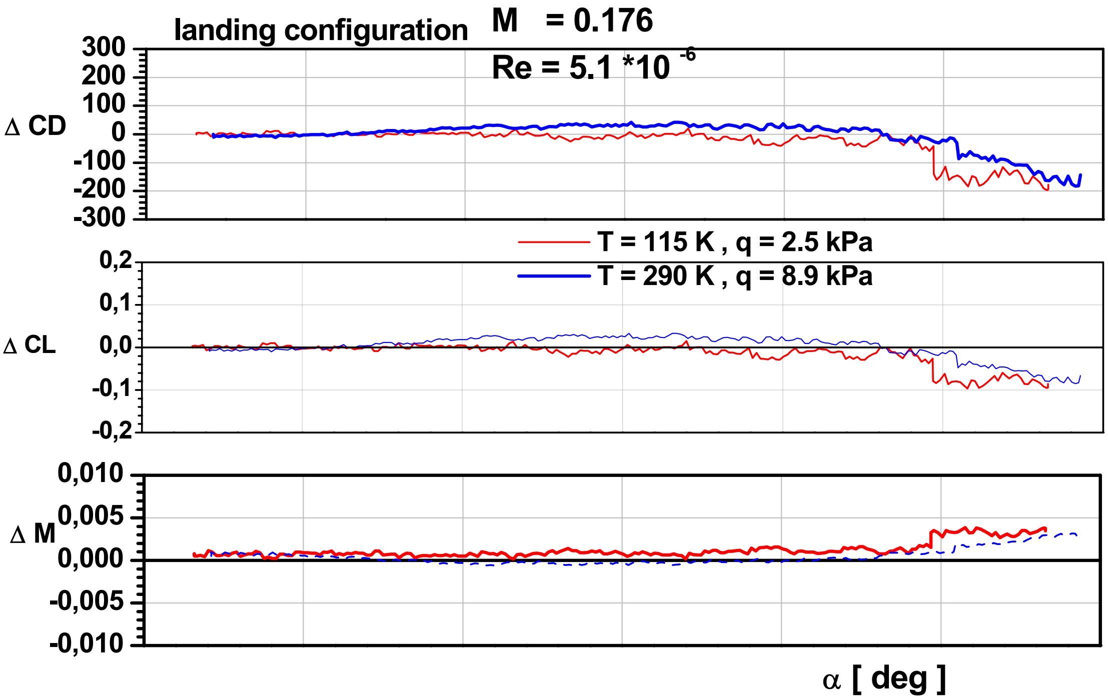


Figure 14 : Variation of dynamic pressure on lift and drag

The same taring procedure has been applied to evaluate increments in drag and lift across each polar. Fluctuations in the dynamic head when pitching the model have been additionally removed by referencing the q-value at the beginning of the polar (assuming a linear correlation for small perturbations). We find a clear trend indicating a steeper rise in lift and drag versus model incidence for the higher level of dynamic head.

With reference to the analysis performed above we conclude that the landing configuration is affected by aeroelasticity. Lift over drag versus lift is presented for the conditions discussed in figure 15 at a Reynolds number which was generated with a different combination of tunnel temperature and pressure. Thus comparing results obtained at the two corresponding levels of dynamic head varied by a factor of about 4, we are faced by a quasi anti-clockwise rotation of the curve when increasing the dynamic head.

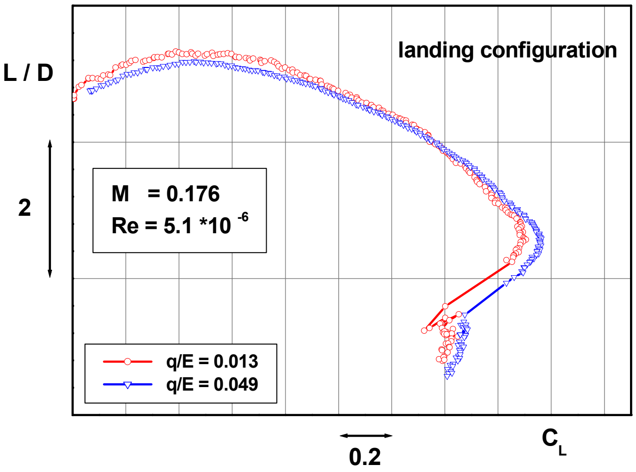


Figure 15 : Lift over drag vs lift for different q-levels

INTERFACILITY AND FLIGHT COMPARISONS

As already outlined, the major objective of the windtunnel entry was to validate ETW for low speed high lift testing. Conclusions should be drawn by referring to results obtained in the Airbus low speed facility LSWT and the DNW-KKK cryogenic tunnel located in Cologne. To ensure a fair and neutral platform for detailed comparisons it had been decided to perform the tests in ETW with all walls closed, hence providing the same test-section configuration as in the other two tunnels. Additionally the identical methodology as applied to the ETW data was used to assess wall interference in the comparative facilities.

On this basis, lift versus model incidence is compared for the landing configuration at the typical Mach number of 0.176 in figure 16. Unfortunately the test capabilities of the LSWT are limited to the indicated Mach and Reynolds number. Despite operating outside of the official envelope of ETW to match the LSWT test condition, a very satisfying agreement was found between both tunnels. When comparing to the un-pressurised cryogenic tunnel KKK, a comparable level of agreement has been found as documented in the figure. Differences of only one lift count can be quoted up to maximum lift.

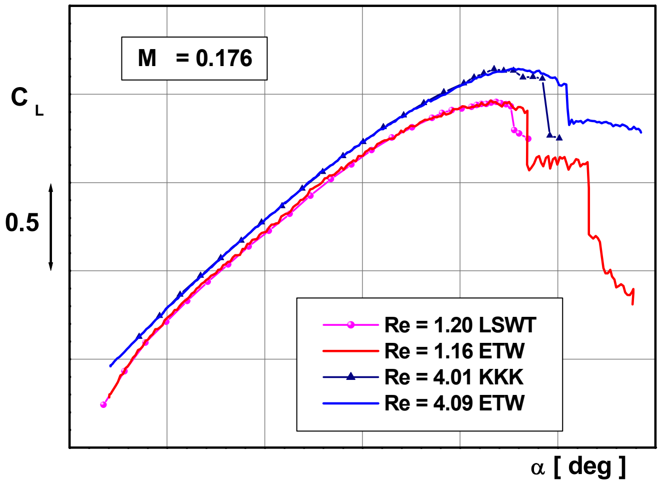


Figure 16 : Interfacility comparison of lift coefficient

It is evident that the flow breakdown causing the lift drop is slightly delayed in ETW compared to the other tunnels. No information is presently available to explain this behaviour which may be a consequence of different flow quality levels and consequently will be kept under consideration.

Beside the interfacility comparison of absolute aerodynamic quantities which is quite challenging anyway, incremental analyses are of major importance especially in the half model business. Figure 17 reflects the finding in incremental drag when referencing the landing configuration to the clean wing model set-up. This procedure was applied in each facility. It is worth to mention that the relevant data were gained in the LSWT tunnel during one entry while the ETW results combine data recorded in two independent campaigns. Here the second entry was performed about 10 months later including a complete model re-assembly. Nevertheless a very satisfying match of the results reveals as presented in the figure. Over the incidence range where the flow is widely un-separated over the wing, maximum differences of only 20 drag counts have been evaluated. This value corresponds to about 1% of the absolute level and covers interfacility comparisons as well as long term repeatability for a test condition outside of the operating envelope of ETW.

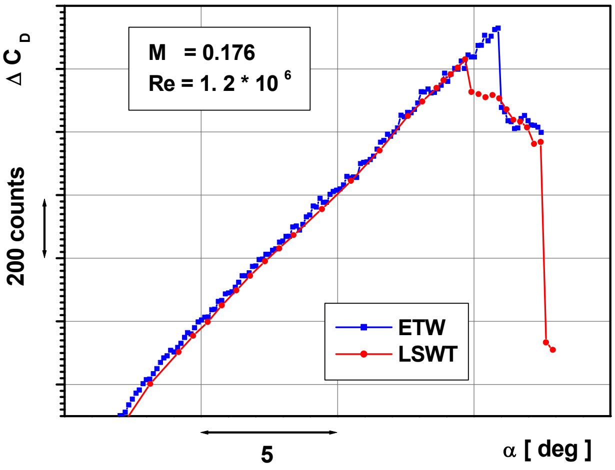


Figure 17 : Interfacility comparison of drag increment

To validate ETW we were able to refer to the LSWT at the lowest and to KKK at intermediate Reynolds numbers. Additionally a limited number of flight data were also available for comparison. Despite the real aircraft being prepared for flow visualisation, the aircraft set-up revealed typical deviations from the windtunnel model. Hence the comparison of separation areas of the flow over the wing has to be seen with respect to the existing differences in geometry.

Figure 18 presents the evaluated zones of flow separation in a simplified form. It is evident that flight data show enlarged areas of separation compared to the wind tunnel results. But as relevant flight test were performed with the landing gear deployed this fact is thought to have affected separation in a negative sense.

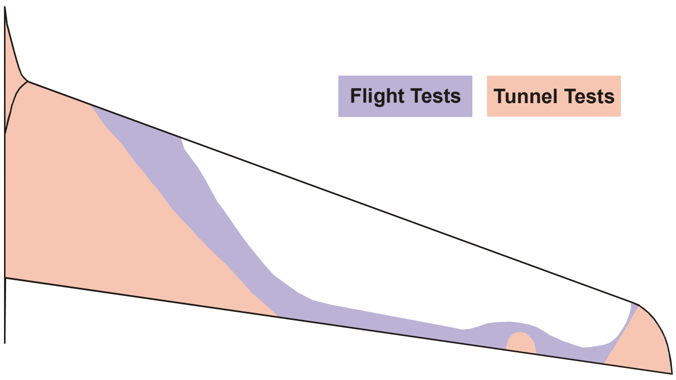


Figure 18 : Flight to tunnel comparison on wing flow separation

SUMMARY

Within the European Research Project EUROLIFT unique windtunnel tests have been performed using a half model suitable for cryogenic pressurised environment The complete Reynolds number range from the lower edge representing the capability of an ambient air facility up to flight conditions was covered in the same entry. A high level of productivity was demonstrated coupled with an excellent data quality proven by comparisons with results from two commercial windtunnels and flight results.

Low speed testing with a clean wing configuration revealed the expected Reynolds number sensitive flow behaviour due to its complex 3d flow development.

The existence of aeroelastic effects could be shown on a landing configuration underlining the importance to own test capabilities allowing to separate pure Reynolds number from aeroelastic effects.

REFERENCES

1 Martin C.N. Wright
Development of the Half Model Testing Capability at ETW
ICAS 2000

2 Quest, J.
ETW – High Quality Test Performance in cryogenic environment
AIAA-00-2206

3 Schimanski, D. & Hefer, G.
Recent Aspects of high Reynolds Number Data Quality and Capabilities at the European Transonic Windtunnel
AIAA-00-0292