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Edited by Winfried Kuehn, Airbus Deutschland, Bremen with support of DAC

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Co-ordinator:	Airbus Deutschland	A-D	D
Contractors:	Airbus France	A-F	F
	Airbus United Kingdom	A-UK	UK
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	Univ. Stuttgart –IAG	IAG	D
	Moscow Inst of Physics and Tech	MIPT	RU

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INTRODUCTION

Despite considerable progress in computational aerodynamics, wind tunnels are still the prime tool to measure and to predict aircraft performance for take–off and cruise, design and off-design conditions However, conventional wind tunnels face physical limits in matching Reynolds and Mach number ranges required to realistically simulate cruise conditions. A means to overcome this limit are cryogenic wind tunnels as for instance, the European Transonic Wind tunnel (ETW).

FLIRET's objective was to improve the accuracy of performance measurements at flight Reynolds number in cryogenic wind tunnels where the highest measuring accuracy is needed to predict the flight behaviour and performance of new aircraft. But there is also a considerable improvement for the handling quality and loads testing. The performance guarantees given to airlines trust to a large extent the accuracy of wind tunnel test data and their extrapolation to flight conditions. Similarly, a high fidelity simulation of the aircraft in the wind tunnel is the best way to avoid aerodynamic difficulties during flight testing and hence reduces the time to market and cost.

FLIRET started on February 2005 focussing on aircraft model mounting techniques in cryogenic wind tunnels since they have a significant influence on high Reynolds number performance measurements. FLIRET investigated several model-mounting alternatives and compared the devices with existing state of the art stings. This approach appeared reasonable since most of the stings used to date had been designed more than ten years ago. With support of state of the art CFD tools it was hoped to achieve a reasonable progress in measurement accuracy.

Another objective of FLIRET was to better integrated CFD simulation capabilities and wind tunnel testing. It was intended to clarify the advantages and the disadvantages of numerical and experimental work to take maximum benefit of synergy effects. The FLIRET approach offered a lot of opportunities for identifying weaknesses of each method and to combine their strengths.

The following work was done:

- Designing and manufacturing of several model mounting devices (stings)
- Applying and harmonising CFD and prediction tools including the numerical meshes
- Analysing the test results of each FLIRET work package
- Analysing the applied model quality, manufacturing and handling strategies
- Deriving recommendations for industrial testing in cryogenic tunnels

During the course of the project, technical reviews were used to update the strategy during the course of the project with respect to mounting device design and testing approach. This allowed maximum flexibility but turned out to be extremely difficult in a project with a fixed budget.

Based on numerical simulation, new and improved designs were used of straight stings, fin stings and twin stings. Ten test campaigns were performed in the ETW, the ETW pilot tunnel and the Aircraft Research Association (ARA) tunnel with four new sting configurations and two existing ones. One test with a new 2D-model and three half model tests were performed. One of them required three different peniches, which ended up in nearly three small, but separate measuring campaigns.

For most of the tested configurations improvements were found. It is estimated that FLIRET managed to raise testing accuracy in cryogenic tunnels, but in particular in the ETW by about 10% with reference to the state of the art at the start of the project. This was demonstrated by utilising FLIRET's new sting configurations. Unsurprisingly, the new stings have each to be used under specific model and wind tunnel conditions. A universal sting which allows excellent measurements under any condition is not feasible. For example, the Minimum Size Straight Sting provides reference data in a limited loads window and the blade sting guaranties very stable model behaviour in the wind tunnel.

ADVANCED BLADE STING

The global objective in the first part of this task was to investigate low interference supports for High Reynolds number testing needed for aircraft performance evaluation. CFD tools were to be employed for the selection of the general arrangement and for the definition of the aero-lines. A complete CFD assessment of sting corrections was planned over a wide range of mach numbers and lift coefficients.

In the second part of this task the objectives were to produce a method for obtaining empennage tunnel measurements at high Reynolds numbers. New model supports had to be developed and assessed as well as the theoretical and experimental assessment of blade sting interference effects and correction rules focusing particularly on tail measurement.

A full design process including a detailed analysis of model/support interferences was performed with two sting designs being selected for detailed analysis of sting interferences. CFD results showed encouraging results showing our ability to reduce the interference between stings and models. This has shown the large benefit from designing a support to the model itself, instead of trying to adapt an existing support. The analysis has also shown the difficulty to define wind tunnel corrections since the efficiency of a support is strongly dependant on the way the correction is defined.

The aero-lines of the Straight and Fin Stings have been worked out leading to the Minimum Size Straight Sting and the Optimized Fin Sting designs. Their performance has been assessed with Navier-Stokes codes and compared to the reference stings. This comparison is showing a clear reduction in the level of interference. The design of the blade sting was successful completed because it keeps free the wing of the model because the blade is attached to the model front fuselage. This was validated in wind tunnel test. The result is the new blade sting which is ready for industrial testing in cryogenic environment.

BUFFET ONSET AT FLIGHT RE AND MODEL VIBRATIONS

The objectives in this area are two-fold:

- Improving buffet onset understanding and prediction
- Investigating on ETW model vibration problems

For improving buffet onset understanding and prediction the first step was to be investigate the capability of numerical tools to predict buffet onset including parametric study of grid refinement, turbulence model effect and using different codes. These numerical means were to be used to determine wing deformation, Reynolds, Mach… effect on buffet onset and separated flow characteristics. In the next step a specific high Reynolds wind tunnel test campaign for buffet onset investigations had to be prepared and conducted. After the test a deep analysis of the wind tunnel test results in term of physical understanding, parametric effects (Reynolds, Mach, wing deformation,) and steady and unsteady pressure characteristics was performed and different prediction methods of buffet onset with wind tunnel test measurements were compared.

For investigating the model vibration problems encountered in wind tunnels, but here particularly in the ETW the effectiveness of the advanced version of an vibration suppression system was to be investigated. During that test potential sources of vibration had to be identified. An aero elastic model of the model mounted on the ETW sting-balance including unsteady aero loads had top be build for simulating the dynamic response of the model in the test section. Finally the dynamic response of the mounting to the unsteady effort due to ETW turbulence and compare it to the model vibration measured during the test had to be quantified.

The conclusions may be summarised as follows:

Investigation on Buffet onset

A large and useful wind tunnel data bank, including unsteady flow measurements have been obtained on realistic aircraft and at high Reynolds numbers. Considering numerical investigations, different simulations have been performed focussing on Reynolds and Mach number. Wing twist deformation was carried out. At the end, all partners' predictions were in good agreement with experiments but with different levels of accuracy with the prediction of buffet onset being in line with the wind tunnel test results.

The parametric study shows that the start of non-linearity buffet onset is not so sensitive to turbulence model and mesh refinement in the range of mesh and turbulence model tested. The CFD analyses demonstrates the influence of the wing twist deformation that is of primary importance for a reliable buffet onset prediction

The wind tunnel test and the CFD analysis confirmed a significant Reynolds effect on buffet onset prediction especially in the range of 6 to 10 millions where there is quite large transition effect. For the highest Reynolds number Re=32 Mio to Re=54Mio a slight effect on the CL of flow separation appearance is observed (DCL ≈ 0.01- 0.02).

Table 1 Delta CL of buffet onset for different Reynolds number

Delta CL of buffet onset	Re=54 Mio transition free
Re=8 Mio with fixed transition	DCL≈0.06
Re=32 Mio transition free	DCL≈0.01- 0.02

A wing twist effect (dynamic pressure effect) has been also identified. When dynamic pressure increases, model deformation increases as well and then the twist becomes nose down (lower local incidence) on the outer wing. Then, the CL buffet increases. The order of magnitude is around Delta-CL ≈ 0.02 for a delta twist at the tip of the wing of around 0.6°, quite representative of flight deformation.

As a result, there is now a better understanding of the Reynolds effect on buffet onset characteristics at high speed.

Model vibration suppression

Pre-tests demonstrated the efficiency of the anti-vibration system which reduced aircraft model vibrations under an acceptable level. The investigation on possible sources of vibrations reached to the following conclusions:

The unsteady flow pattern in a cavity at the model / sting interface could be a source of the vibration. CFD investigations and wind tunnel test analysis have shown a very complex 3D/unsteady internal flow driven by rear end geometry. The complexity of the phenomenon and the current limited information of the unsteady flow characteristic don't allow concluding in the frame of FLIRET. Further investigations are required.

Another potential excitation of the model is the wind tunnels atmospheric turbulence. Two different modellings have been performed: the first based on the unsteady measurement on the wing and the second on the pressure fluctuations measured in the holes of the wind tunnel test section. Unfortunately the pre-test wasn't optimised for ETW vibrations. The modelling developed by Airbus using the unsteady sensor on the wing delivered quite low excitation levels which can't explain the model vibration. An simulation using the pressure on the wall delivered relatively high level of vibration when using the aerolastic model. Therefore it is difficult to conclude at this stage and further investigations are required.

Despite the fact that there is not enough information for conclusions, associated to the cancellation of the specific test the FLIRET investigations allow to improve our understanding of the problem and to identify some potential source and eliminate some others and to give some recommendations in order to improve the situation.

HIGH LIFT BEHAVIOUR OF HALF MODELS AT FLIGHT REYNOLDS NUMBERS

Testing of high lift aerodynamics at flight Reynolds numbers in the ETW can only be performed using wind tunnel models based on the half model technique. Thus high Reynolds numbers up to 30 millions are achievable. At these tests two principle problems can occur:

- The boundary layer development on the model can be influenced by the surface roughness of the model
- The wind tunnel wall as the mirror plane of the half model is covered by the wall boundary layer influencing the flow conditions of the model.

From the global main objective to improve the ETW wind tunnel technique regarding the half model high lift behaviour at high Reynolds numbers the following objectives have been formulated in FLIRET:

- To assess the value of influence of surface roughness on the boundary layer with respect to laminar-turbulent transition, re-laminarisation and turbulent boundary layer drag.
- To define criterions for surface roughness having well known or no impact on the boundary layer development
- To assess the physical mechanism of interaction of the boundary layer of the model mirror wall of the wind tunnel and the flow around the half model
- To define criterions or conditions for low interference of model mirror wall boundary layer and model flow

- To extend existing wind tunnel wall corrections rules with regard to the influence of the boundary layer of the model mirror wall.

Test cases for the 2D-ETW pilot tunnel test based on roughness definition reviews and investigations of roughness implementation into turbulence models of CFD codes have been selected. Here a strategy for the experimental investigations has been developed in cooperation with the partners involved. Supported by boundary layer analyses it resulted in the definition of a 2D test airfoil equipped with pressure taps, temperature sensitive paint and a Piezo-array.

The progresses achieved can be summarised as follows: The simulation of surface-roughness effects for turbulent flow cases has been performed successfully by numerical activities. Further numerical work has been done on roughness effects regarding the K3DY model tested within this task. Additional support could be given for the better analysis of the results from the ETW pilot tunnel roughness test. The analysis of test data from the ETW pilot tunnel test (temperature sensitive paint and piezo tests) has been successfully done.

Concerning half-model mounting effects on the flow characteristics in the ETW test section the following statement can be made:

- The ETW tests with a cryo-half model with different peniche heights have been conducted successfully up to Reynolds numbers of 25 millions delivering excellent experimental data.
- The mounting effects for clean and high lift configurations could be numerical assessed using structured and unstructured CFD code based on Reynolds equations , time averaged Navier-Stokes equation) simulations of the DLR model in the ETW test section.
- The experimental data gained have been served for CFD validation and for comparison.
- The evaluation of both, experimental and numerical data led to proposals and recommendations for half-model testing at high Reynolds numbers at high lift conditions.

It was possible to establish surface finish requirements for models to be tested at high Reynolds numbers which are important for future tests.

The knowledge about surface finish requirements for high Reynolds number testing gained led to a better understanding of the boundary layer characteristics being responsible for the measured lift behaviour. The results show that the present CFD methods are able to consider surface roughness and transition prediction at least on clean wings at maximum lift. The findings will contribute to allow cost savings on model manufacturing and to develop concepts for the prediction of maximum lift in free flight.

The excellent data base achieved experimentally and numerically enables proposals and recommendations to derive principles for half model testing at flight Reynolds numbers at high lift.

The following conclusions can be drawn:

- No half model-peniche configuration for a high lift at high Reynolds number testing can match the free flight result because the major inboard peniche influences as flow displacement and aspect ratio effect which dominate the half model flow strongly interfering with the tunnel wall boundary layer.
- The experimental and numerical results show that the complexity and the non-linearity of the peniche model flow doesn’t allow a correct wind tunnel correction as applied in today’s wind tunnels
- An improvement of correction methods seems to be not feasible.

- The results of this task clearly demonstrate that only the use of validated CFD methods can open the possibility to compare the wind tunnel test with the free flight condition. The use of the “Numerical Wind Tunnel” i.e. the numerical simulation of the complete wind tunnel flow and the concerning free flight model can be the way out.
- Improved correction rules for half model testing based on the evaluation of the numerical and experimental results are afflicted with problems and only possible by the use of the “Numerical Wind Tunnel”.

OUTLOOK

After 42 months FLIRET was successfully completed. Several sting designs have been updated with the respective hardware available now. This is of benefit to all those companies which rely on cryogenic testing and in particular on the ETW for the development of aircraft.

The results are also important for the tunnel operator as the state of the art technology is now available for the aeronautics industry.

The findings of FLIRET are further analyzed in the EU project ALEF which performs aerodynamic loads estimation at extremes of the flight envelope. ALEF started in May of 2009 for three years.

Several investigations not covered in FLIRET are continued in the EU-project DESIREH which is focussed on cryogenic low speed testing under industrial conditions which is further developing testing tools to validate high end CFD work by the wind tunnel results. DESIREH started in March 2009 running for four years.

Due to the ever increasing level of CFD work in aircraft design it is strongly recommended to further optimise the cooperation between the generation of CFD and experimental results. It allows optimizing the technologies, maximising the benefits from both approaches i.e. in the risk mitigation during aircraft design. It also allows a deeper understanding of the dynamics of the flow which cannot be achieved by one method alone. It is difficult to quantify the latter aspect but the physical understanding of the flow physics is the basis for all aircraft design.

It should be mentioned that the results and some of the hardware developed in FLIRET is utilised in the daily testing procedures.

ACKNOWLEDGEMENTS

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ANNEX: LIST OF PUBLICATIONS

AI-D	ECCOMAS Venice, 7.5.2008: Flight Reynolds Number Testing - The European Project FLIRET
DLR	STAB: Project ForMEx - A new CFD approach for transposition of Wind Tunnel data towards Flight Conditions.
DLR	ICAS: A new approach in CFD supported Wind Tunnel testing
DLR	RTO, AVT-147: CFD Validation by Wind Tunnel Measurements: Uncertainty Assessment by Numerical Simulation of Complete Wind Tunnel Flows
DLR	3rd joint EWA workshop: "Simulation of the flow around a Model in the transonic wind tunnel ETW"
ETW	AIAA Orlando, Jan.2009: Flight Reynolds Number Testing at ETW -The European Project FLIRET
ONERA TsAGI TKK AI-UK	Buffet onset prediction in the FLIRET programme
IMP IAG DLR	TASK QUARTERLY, vol. 10, no. 2, 2006, pp. 191-206, "High-lift behaviour of half models at flight Reynolds numbers"
IMP IAG DLR	HPC Europa Transnational Access Meeting, Barcelona, "High-lift behaviour of half models at flight Reynolds numbers"
IMP IAG DLR	HPC Europa Report, Science and Supercomputing in Europe, report 2006, "High-lift behaviour of half models at flight Reynolds numbers"
IMP AI-E ONERA	XVIII National Polish Fluid Mechanics Conference, Jastrzębia Góra, Poland, "Numerical analysis of support system influence on aircraft model aerodynamic characteristics"
TU-Berlin	Measurement of Unsteady Surface Forces by Means of Piezoelectrical Copolymer Coatings
TU-Berlin ETW	AIAA 2008-842, Jan. 2008, Reno, On Application of Surface Measurement Techniques for Cryogenic High Reynolds Number Investigations on Wind Tunnel Models
TU-Berlin	Bildgebende Erfassung instationärer Wanddruckfelder mit Hilfe von drucksensitiven Copolymerbeschichtungen
IAG	Optimisation of Supports for High Reynolds Number Testing

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