# 46th AIAA Aerospace Sciences Meeting and Exhibit RENO, 7-10 January-2008 High Reynolds Number Aerodynamics & Testing

# <u>Title</u>: **The FALCON 7X: from ETW to flight** Paper AIAA-2008-0835

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# Nomenclature

AoA	=	Angle of Attack
с	=	chord
CFD	=	Computational Fluid Dynamics
Cm	=	Pitching moment coefficient
$C_p$ or $Kp$	=	pressure coefficient
Ċx	=	Drag coefficient
Cz	=	Lift coefficient
Ε	=	Young's Modulus
ETW	=	European Transonic Wind tunnel
FLIRET	=	Flight Reynolds testing
HTP	=	Horizontal Tail Plane
KULITE	=	Unsteady pressure transducer
M∞	=	Free stream Mach number
MDM	=	Model Deformation Measurements
ONERA	=	French Aerospace research laboratory
Pi or Ptot	=	Total Pressure
PMR	=	Point of Model Rotation
PSP	=	Pressure Sensitive Paint
q	=	Dynamic pressure
RANS	=	Reynolds Average Navier-Stokes computation
SCAB	=	Sting CAlibration Body
Ti or Ttot	=	Total Temperature
WT	=	Wind Tunnel
WTT	=	Wind Tunnel Tests
WBS	=	Work Breakdown Structure
Z Sting	=	Blade Sting

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1 American Institute of Aeronautics and Astronautics Paper AIAA-2008-0835

# I. Introduction

The FALCON 7X wind tunnel tests at ETW were carried out in July 2006 on a full model in the framework of the European program "FLIRET" (standing for **FLI**ght **RE**ynolds Testing) within Work Package 1 ("advanced model support"), see figure 1. This entry took place more than one year after the first flight of the aircraft.

The main objective of this test was to investigate the validity of the WT data compared to real flight conditions. In order to match this high level of requirements, DASSAULT, as Workpackage leader, had to combine the following issues:

- (1) to perform a test at ETW, one of the most advanced transonic wind tunnel facility capable of simulating flight conditions in terms of Reynolds number;
- (2) to design a dedicated mounting consisting of an optimized blade sting to minimize flow interaction on the model after body part;
- (3) to take into account this support interaction by the help of Navier-Stokes CFD tools (thanks to ONERA who proposed a methodology to correct raw data and produced a full set of data);
- (4) to use the best available tools ie the most modern measuring techniques to assess wing deformation (performed with the "MDM" system, the Model Deformation Measurement system)
- (5) to design and manufacture a dedicated model equipped with a set of static pressure ports and a set of unsteady pressure transducers to assess buffet onset occurrence.

All these topics will be accurately detailed in this paper. At the end, the main results will be presented including flight tests versus wind tunnel testing comparisons. Our objective is to provide the ground to flight extrapolation for future projects. This philosophy allows us to have a better understanding and to get the best evaluation of the remaining gap between wind tunnel and flight. The aim of this activity is to establish better predictions for the next generation of civil aircraft programs, thus minimizing the level of uncertainty during development phase and limiting the industrial risks to minimum.



### II. Context/Objectives

The first flight of the Falcon 7X and the flight test series that followed have been the opportunity for DASSAULT- AVIATION to validate predictions from high complexity 3D Navier-Stokes computations and extensive wind tunnel test campaigns. Most of the wind tunnel aerodynamic data produced prior to the first flight of the F7X did rely on test campaigns conducted in conventional wind tunnels (i.e. non cryogenic), using the long experience of DASSAULT- AVIATION in aircrafts conception to integrate the scaling effects to be considered between wind tunnels and flight.

In order to minimize the level of uncertainty between predictions and flight, the use of the most advanced tools available is becoming essential to the conception of competitive aircrafts with increased security, comfort, manœuvrability and minimised fuel consumption. This includes the use of the ETW (European Transonic Wind tunnel) in the development of all our future projects.

With its ability to control total temperature from ambient down to 110 K and total pressure from 1.2 to 4.5 bar, ETW is the only European wind tunnel capable of Reynolds flight number simulation. Therefore, a high interest was existing after the first flight of the F7X to perform a test campaign in 2006 with a 1/16 model of the F7X in the ETW facility (see figure 2), thus allowing to establish a complete database in the highest fidelity ground testing facility. The tests were conducted in the framework of the FLIRET European project, one of the main objectives being the design and manufacturing of an optimised blade support to minimize flow interference between fuselage and support. As



a result, sting interference corrections were reduced to minimum. As part of the FLIRET project, ONERA did produce the near-field sting interference corrections for the considered test cases by CFD computations.

# III. Test Set-up

### A. Overview of the facility

The ETW facility is a transonic, closed-circuit cryogenic wind tunnel. The test section is 2 m high, 2.40 m wide. Temperature can vary from ambient to 110K, total pressure from 1.2 to 4.5 bar, the Mach number from 0.15 to 1.3. Pure nitrogen is used as the test gas.



The high quality of the ETW flow control allows the parameters to remain constant during testing: Mach number stability is better than  $\pm 0.001$ , total temperature fluctuations are within  $\pm 0.25$  K, dynamic pressure variations are

3 American Institute of Aeronautics and Astronautics Paper AIAA-2008-0835 kept below  $\pm 150$  Pa for all test conditions. Together with state-of-the-art instrumentation, this offers ETW outstanding capabilities to deliver high data quality at flight Reynolds number, thus minimizing the remaining uncertainty between wind tunnel tests and flight.

The capacity of ETW to vary independently temperature, pressure and Mach number has been taken into account in the definition of the test matrix. Indeed, a proper choice in the flow parameters can allow to study pure Reynolds number effects (by variation of total temperature with constant q/E, E being the Young's modulus) as well as pure aeroelastic effects (by keeping Reynolds number constant with the appropriate choice of Ttot and Ptot).

### **B.** Test envelope

Figure 4 shows the test envelope of the F7X test programme for the Mach number of 0.8. Design point (and model jig shape) is at 16 million Reynolds number for a total pressure of 3 bars. The Mach number was varied during tests between 0.500 and 0.900.

Test parameters have been chosen in order to allow the study of pure Reynolds number effects (at low pressure level) as well as pure aeroelastic effects (at the Reynolds number of 16 million).



### **IV.** Test instrumentation

#### A. Model forces and moments, Model attitude

The F7X full model used during this FLIRET test campaign was mounted on a 6-components cryogenic balance. Full model balances used at ETW are regularly calibrated over the complete temperature range that can be reached by the wind tunnel flow. Accuracy of the balance is 0.1% of the maximum loads. Typically, data repeatability for drag is below  $\pm 1$  drag count.

The inclinometer, coupled with an accelerometer, measures the angle of incidence with an accuracy of  $[+0.002^{\circ}, -0.0005^{\circ}]$  within the model incidence range.

### **B.** Pressure measurements

The F7X model was fitted with more than 170 static pressure ports on nacelles and starboard wing, thus allowing accurate pressure distribution measurements over the wing. Pressure measurements are performed with an accuracy of better than  $\pm 150$  Pa (PSP is not yet available at ETW).

In addition to the static pressure measurements, dynamic pressure measurements were conducted by installing 31 Kulite dynamic pressure sensors on the port wing (plus one installed on model nose for reference). The ETW High Speed Data Acquisition System (HSDAS) performed recording and complete post-processing of the dynamic data.

#### **C. Model Deformation Measurements**

Considering the outstanding progress made in CFD computations over the past decade, accurate determination of wing twist and bending has become a topic of major importance in wind tunnel testing. A proper analysis of wind tunnel data and correct comparison to numerical computations can only be performed with the accurate evaluation of model deformations, which requests the use of adapted measurement techniques, capable of delivering accurate results with little or no time delay (on-line data).

The capability of the European Transonic Windtunnel to separate pure aeroelastic effects from pure Reynolds number effects is emphasized by the use of the Stereo Pattern Tracking system (SPT system) developed by ETW.

The SPT system is an optical measurement system capable of accurate wing deformation measurements. It can also be adapted to half models  $[^2]$ .

The principle of the system is rather simple, as the setup itself. The optical system, made of two cameras positioned behind windows from the test section walls, focuses on dots distributed on two



lines along the leading edge and trailing edge of the wing. The density of the dots is higher towards the wing tip region to compensate the shortening of the chord, and thus still guarantee a good accuracy around this region. These

<sup>5</sup> American Institute of Aeronautics and Astronautics Paper AIAA-2008-0835

markers have a diameter of 20 mm and a thickness of 5  $\mu$ m. The system needs to be calibrated, which is made with a special frame fitted with light bulbs at precise locations. The bulbs are identified by the cameras and linked to their 3D coordinates, resulting in the calibration of a volume around the wing. The displacement of the dots during testing (model pitch + wing deformation) is processed by the system, which delivers online information about twist and bending along wing span. Twist angle evaluation is given with an accuracy better than 0.1°.

Measurements were conducted for the two levels of total pressure included in the programme. This SPT system was used in parallel with the ETW analytic method for wing deformation measurement (see AIAA paper nr. 2002-0310 [ $^3$ ]). This method is based on wing pressure measurements for a constant Reynolds number and different pressure levels.

The following figure gives a comparison of wing twist evaluation from the SPT system and from the analytical method based on model static pressures measurements for different lift values at Mach 0.8, Ptot=3 bars. The deformation observed for this test case is similar for any test point situated on a iso-q/E line from the test envelope.

On top of this, the Kulites installed on the port wing were used to derive an information on wing twist and bending. A proper control surface and lever arm was allocated to each Kulite, thus allowing to derive deformation evaluation.

As a result, model deformation was assessed by three independent methods.

## V. Sting Correction

#### A. Generalities

When simulating an aircraft configuration in a wind tunnel, it is necessary to consider among other corrections (as flow angularity, cavity effects,...) the support interference effects. Indeed, attaching the model introduces both a change in the aircraft geometry - to let the sting enter the model - and obviously a flow alteration due to the intrusive support system. These disturbances are small due to the optimization of the sting itself, however the effects can be corrected.

The downstream mounting generally slows down the upstream flow. Close to the model, the velocity is reduced by a few thousands of Mach number. In experiments as well as in computations, it is therefore necessary to increase the upstream "free" flow velocity to recover the correct desired Mach number on the model. This increase in Mach number is called  $\Delta M=M'$  - M in the following lines.

Similarly, non symmetrical devices as the blade sting mounting induces a change in AoA on the model (generally a few hundreds of a degree). Therefore, the model geometrical AoA should be adapted by  $\Delta\alpha = \alpha' - \alpha$  to compensate for this local change in flow angle.

In ETW, the Mach number reduction is assessed by a combination of calibration measurements and computations. The representative values chosen for  $\Delta M$  is the Mach number reduction at the point of model rotation.. CFD "Euler" were shown to be accurate enough for that purpose. A good agreement has been observed between CFD and SCAB measurements. Mach number as well as AoA corrections are detailed on figure 6.



Figure 6: Mach number(continuous lines) and AoA (dashed lines) deviations at PMR deduced from sting alone Euler computations

#### **B.** Description of the procedure



The computation procedure proposed by ONERA is summarized as sketched here below: (figure 8)

For a given Mach number  $M_{\infty}$  and incidence  $\alpha_{\infty}$ , the procedure is:

1. To compute flow disturbance caused by the sting alone at  $M_{\infty}$ ,  $\alpha_{\infty}$  (Euler computation of the sting in freeflow). To probe Mach number  $M_{\text{PMR}}$  at PMR to compute  $\Delta M = M_{\infty} - M_{\text{PMR}}$ . In the same way, to probe angularity at PMR  $\alpha_{\text{PMR}}$  to compute  $\Delta \alpha = \alpha_{\infty} - \alpha_{\text{PMR}}$ . Probe pressure along the model centreline (where pressure is normalized over  $p_{\infty}$  and  $q_{\infty}$ ).

2. To compute the model without sting at  $M_{\infty}$ ,  $\alpha_{\infty}$  (model in free-flow). Reference dynamic pressure for force coefficients is  $q_{\infty}$ .

3. To compute the model with sting (model on sting in free-flow) at corrected Mach number  $M_{\infty} + \Delta M$  and at the incidence  $\alpha_{\infty} + \Delta \alpha$ . Reference dynamic pressure for force coefficients is  $q_{\infty}$ .

4. To integrate pressure distribution from "1" with model cross-section distribution to derive axial buoyancy force and subtract it from axial force in "3".

5. Finally, comparison between simulated model in free-flow and simulated model on sting corrected from far-field contribution yields the near-field effects.



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The flow around the Falcon tested in ETW was accurately modelled, delivering good agreement between computational results and experimental measurements, mainly limited by wing bending. No blade sting effects occur on wing schock location (see figure 10).



Applying the method described here above allowed to derive the effect of the Z-sting support on the flow and the corrections to be applied to force coefficients. This effect was shown to be weak at Mach number below 0.9 (see figure 11). The near-field effect of the sting increases the lift of the aircraft. Drag and pitching moment are modified in such proportions that the performance curves are nearly unchanged. Sting effects were interpolated to build a complete dataset of corrections that was delivered to ETW prior to the test entry, allowing real-time corrections.



VI. Test results/ lessons learned

Having produced the corrected wind tunnel results, the next step was to compare with the available flight data. For this purpose, the windtunnel balance measurements were modified by calculations based on model deformations acquired during the test campaign. The resulting dataset corresponds to measurements which one would have obtained by testing a theoretical "rigid" windtunnel model (ie with no wing shape variation with dynamic pressure or angle of attack). Figure 12 shows in black an example of fully corrected data obtained from wind tunnel testing, and in blue the corresponding data calculated for the same test conditions on a theoretical rigid model.

In a similar manner, flight test data were altered to simulate the behaviour of a rigid aircraft in flight. These modified flight test data appear in



8 American Institute of Aeronautics and Astronautics Paper AIAA-2008-0835

red on Figure 12. One must stress that the red curves shown here are mean values taken from numerous flight test data acquisitions. The original set of data consists in a significant amount of test points including some scatter. Uncertainty is reduced to minimum by using a statistical approach, resulting in a large amount of datapoints.

Basically, the agreement between wind tunnel and flight on the rigid aircraft is very good for the lift coefficient. The agreement is very good for the lower part of the pitching moment as well, and the deviation observed at higher angles of attacks can be attributed to the level of uncertainty of the method. Considering the data discrepancy from flight tests however, the agreement can be considered as very good for pitching moment.

The following figures show another type of comparison between wind tunnel an flight data. The results from figures 13 and 14 are on the one hand raw data coming from flight (green squares), and on the other hand modified wind tunnel data. Wind tunnel data was first modified as in Figure 12, by computing results for a theoretical rigid model. Then, the wing deformation computed for the real aircraft in flight conditions was applied to the rigid wind tunnel model, thus allowing a direct comparison with flight test raw data.

Once again, under consideration of the flight test discrepancy, the results show a very good agreement both for lift coefficient and for pitching moment.



Figures 15 and 16 show two more comparisons between wind tunnel and flight results. Figure 15 shows a comparison of the HTP efficiency for two settings ( $-2^{\circ}$  and  $-4^{\circ}$ ). As in the previous figures, the wind tunnel data was computed to match the wing deformation from flight (results have been calculated for a stabilized aircraft attitude). High Reynolds number wind tunnel data is matching pretty well the data obtained from flight tests for the four Mach numbers considered and both HTP settings. On figure 16, the comparison between wind tunnel and flight is made for the assessment of buffet onset occurrence. Again, a very good agreement is observed for both sources of information.



## VII. Conclusion

For the first time, DASSAULT-AVIATION has conducted wind tunnel tests at flight Reynolds number on a full model for direct comparison with flight. Thanks to high quality data, the ETW test campaign allows to bridge the gap between wind tunnel and flight by minimizing uncertainties linked to Reynolds number effects. The FLIRET project gave the opportunity to optimize the sting blade support and thus to reduce the magnitude of the support corrections and the associated uncertainty.

The study conducted here with the F7X paves the way to the development of better prediction process for future projects. The gained experience allows significant progress in the understanding of wind tunnel to flight transposition. Cryogenic wind tunnel testing has turned out to be essential in the development of a new aircraft, and will systematically be included in all future aerodynamic work plans.

First of all, the lessons learned of the ETW tests are promising due to a high reliability of the data. The results are consistent and repeatability was excellent during the whole of the test campaign: for example,  $\pm 1$  drag count.

One of the main issue is that both ETW data and flight data cannot be compared directly. ETW data and flight data must be reduced separately before to start the comparison process. Obviously, wing deformation is fully different between the model and the aircraft. Taking into account the MDM (described in §4), a rigid aerodynamic data base "ADB" can be built from the WT results. The second step is to perform the same work with the flight data but the difficulty is higher than previously. Before to built a rigid flight ADB, the extraction of stabilized data in a "cloud of points".

As shown on the previous pictures, ETW data match pretty well flight data with respect to the buffet onset, the lift slope as well. Same nice comparison occurs on the longitudinal stability in the linear part. At higher lift, a large discrepancy appears due probably to a poor modelization of rigid law.

# Acknowledgments

"Both Authors thank ONERA for their contribution in the process of sting correction, the whole ETW staff as well for their involvement to provide high fidelity data"

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