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"Business jet type configuration @ ETW"

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1. Nomenclature

c	=	aerodynamic chord
Rey	=	Reynolds number reduced on the aerodynamic chord
Ps	=	static pressure
Pi0	=	stagnation pressure
Ti0	=	stagnation temperature (kelvin)
$M\infty$	=	Mach number
C_{pi}	=	pressure coefficient on pressure port "i"
Cx1	=	force coefficient in the *x* direction
Cy1	=	force coefficient in the *y* direction
Cz1	=	force coefficient in the *z* direction
Cxv	=	drag coefficient
Czv	=	lift coefficient
Cmv	=	pitching moment coefficient

2. Introduction

ETW (the European Transonic Windtunnel) has been extensively used by DASSAULT-AVIATION in the frame of a new business jet type configuration, the so called "FALCON 7X". The performance specifications for the FALCON 7X were considered as a real challenge by the aerodynamicist team.
The major challenge lies in the design of a new wing, which will equip the complete family of our future FALCONS.
The complexity of the aerodynamic phenomena required the establishment of a new approach in aerodynamic design: the intensive use of the most advanced CFD, together with the most modern windtunnel tests and technical means, like ETW.
The combined use of the most elaborate theoretical analysis and the direct comparison with the most modern experimental results allow a reduction of the total number of iterations before characterizing the final wing shapes selected for the aircraft.

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ETW allows to simulate on reduced-scale models the actual flight conditions of an aircraft cruising at high altitude. This windtunnel is particularly suited for the validation of a new wing and the improvement of the understanding of local characteristics.
The progress made in numerical modelization and experimental techniques are perfectly complementary: the tests at ETW allowed validation of the design choices for the new falcon 7X wing, and validation in the finest details of the actual accuracy of the computation results. Without this cryogenic windtunnel, it would be impossible to know the reliability and applicability limits of the numerical models.
The results obtained in early 2002 at ETW confirmed the pertinence of our new approach. The comparison between tests and computations has been very satisfactory and has validated the methodology for the use of numerical modelization. The knowledge of the performances at real flight conditions allowed an improvement of the operating modes and of the transposition rules for all the traditional windtunnels used through the complete development of the Falcon 7X.
The final definition of the aircraft is a long and hard process, and there is no 100% guarantee of success until the first flight tests planned in 2005, however the results obtained so far are very promising.

Figure 1. An artist view of the future FALCON 7X

3. The main features of the FALCON 7X, a brief historical review

The FALCONS owe their commercial succes over the last 40 years to the reputation of DASSAULT airplanes in many areas, including the quality of aerodynamic design. Aerodynamics determines an airplane's performance, flight qualities handling. All are areas of strength for the airplane relative to the competition. In light of our reputation, the performance specifications for the FALCON 7X are a real challenge for the aerodynamic engineers. They include:

- A fast cruise speed at Mach 0.85, against 0.80 for a FALCON 900EX (the top current bizjet)
- Enhanced efficiency throughout the flight envelope, to achieve the specified flight ranges (5700 nm at Mach 0.80)
- A roughly 35% increase in lift at the top of the climb, for a first increment altitude of 11000 feet, or a gain of 4000 feet over the FALCON 900EX
- Low speed lift such that the airplane can access short runway airports despite its size, so that it can be used as flexibly as a FALCON 900EX

The major challenge for the FALCON 7X lies in the design of a new wing. The results will be capitalized on four decades. The new airfoil will carry our whole family of FALCONS, the way the FALCON 50 wing system, designed in 1975, carried all our business jets until the recent FALCON 900EX and 2000EX's.

Figure 2. Family of FALCONS , *FALCON 50EX, FALCON 2000EX, FALCON 900EX*

4. The aerodynamic design of the FALCON 7X

The performance specifications for the FALCON 7X have spurred us to design a new airfoil architecture (see figure 3). It features:

- Increased leading edge sweep angle
- A higher wing aspect ratio (the wing span characteristic) as well as thin sections

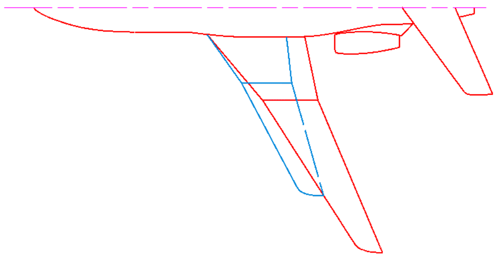

Figure 3. plan views comparison , *FALCON 7X, red line, and FALCON 900EX, blue line*

The plane's cruise speed optimal or economical increased from Mach 0.80, to Mach 0.85 requires a higher leading edge sweep angle in order to reduce the compressibility drag (in extreme cases, supersonic aircraft have a "delta" shape with a very high sweep angle). On the other hand, high sweep angles have a negative effect on the behavior at low speed: the solution is to increase the wing aspect ratio, or ratio of wing span to surface area. The total lift force, or "Czv", is similar, to allow reduced approach speed and short takeoff and landing distances.

An induced effect of choosing a high wing aspect ratio and thin wing sections, combined with optimized and therefore light structural design, is uncommon flexibility. The new, more flexible airfoil is subjected to significant stress in flight because of its increased lift, which causes considerable deformation. In exchange, the airplane's performance and stability are affected by the way the wing's geometry is modified in flight by the aeroelastic effect (see figure 4).

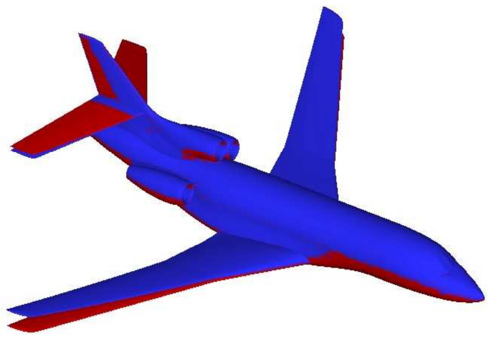

Figure 4. aeroelastic effects on FALCON 7X , FALCON 7X on ground, the red one, FALCON 7X in flight, the blue one

The complex phenomena involved forced a new approach to aerodynamic design. Therefore, an intensive use of the most advanced computer software Navier-Stokes 3D (code AETHER developed by DASSAULT engineers) plus the most modern wind tunnel testing techniques and tools , such as ETW (European Transonic Wind tunnel) are required.
In such a program, the major objectives are both:

- To minimize the cruise drag
- To postpone the buffet onset

5. The aerodynamic strategy - workplan

ETW has been used at an early stage of the aerodynamic workplan during the so-called design phase.
Generally ETW is used during the final check out of the aerodynamic work plan or identification phase to perform the final aerodynamic data base and/or the windtunnel to flight extrapolation. It was an opportunity to use this facility differently. Our wishes were to guarantee as soon as possible the preliminary choice done by CFD.
The complex air flow around the FALCON 7X (see figure 5) and the desired level of performance called for the use of very advanced simulation softwares. These programs solve "Navier-Stokes" equations with turbulence model.

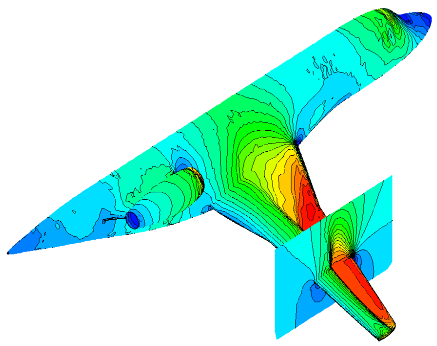

Figure 5. Navier-Stokes computation *, showing the complexity of the flow phenomena in transonic regime*

In spite of the spectacular progress in CFD there is still a strong need to validate the computer codes by comparison with experiments. The first validation step is the assessment of the code numerical safety and the physical models accuracy. For example, which turbulence modeling should be used?

In the past, the predictive methods were validated by comparison of the computed results with well proven methods, the measured "global quantities", such as forces and moments.

The experiments can be put into a database which will be precious to help in developing reliable and accurate codes.

ETW provides a set of modern measurement techniques allowing a precise and thorough description of complex separated flows, strongly interacting and shock separated turbulent boundary.

"The best tools for the best product" means the use of the most advanced CFD Navier-Stokes associated with the most modern facility "ETW".

6. The ETW cryogenic wind tunnel

The ETW wind tunnel is located near Cologne, Germany. A modern testing facility jointly funded and managed by France, Germany, the United kingdom, and the Nederlands, the tunnel was initially designed for Airbus commercial aircraft programs. The ETW went into service in 1993 and the first industrial tests occured in 1998. It's a world class wind tunnel that can simulate on reduced scaled models the real flight conditions of an airplane cruising at high altitude or during take-off /landing phases. Flight conditions are represented by the Mach number , which is the ratio of an airplane's velocity to the speed of sound, and by the Reynolds number, an advanced ratio describing the flow viscosity that is essential in fluid mechanics. The Mach number as well as the Reynolds number are the so called **scaling parameters**. Since the Reynolds number is proportional to the size of the model, "traditional" wind tunnels cannot yield the highest values seen in full scale airplanes in flight. So, engineers "sensivity" is mandatory to correct the results using empirical laws of transposition.

To match the flight Reynolds number or reproduce the viscosity phenomena, we can both increase the stagnation pressure and/or decrease the stagnation temperature of the upstream flow conditions. ETW is a so called **Cryogenic wind tunnel** able to regulate the stagnation temperature down to very low levels, 100 Kelvin or -160°C generated by a pure nitrogen circulation. Under the combined effect of the pressure and temperature, gas density increases enough to recreate exact flight conditions on a given model's scale (an other important point is the capability to adjust separately the pressure and the temperature as we will see later). This requires an electrical power of 55MW. In addition, the liquid nitrogen used to keep temperatures at 100 Kelvin can reach 150 kg/s, or the equivalent of 20 semi-trailers per hour!

DASSAULT-AVIATION first used ETW for the FALCON 7X program. The wind tunnel is especially well suited to validating new wing and shedding light on local phenomena such as the boundary layer behavior done by infrared thermography (see figure 6).

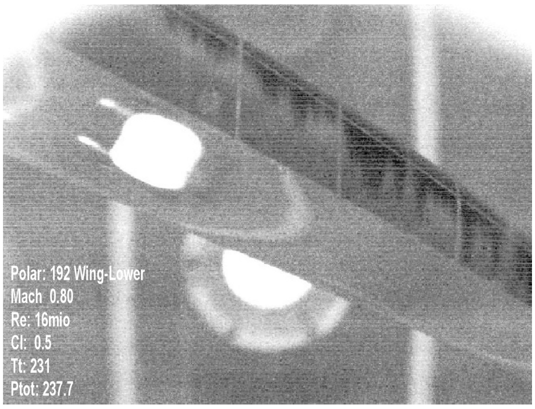

Figure 6. infrared measurement on the model, *to analyse the boundary layer on the trailing edge, dark is laminar behaviour and clear means turbulent behaviour*

7. Test setup and main results

Half model testing has been chosen in order to focus on the operating mode of the wing (see figure 7). The main driving idea was to manufacture the biggest model to have room to install a lot of transducers.

Therefore, a generic model without horizontal tail plane has been built and equipped with a lot of transducers (see figure 10).

- Static pressure ports are mandatory to get the pressure distribution on the wing (the pressure sensitive paints or PSP are not yet available in such a facility due to the use of Nitrogen).
- The buffet onset is obtained by processing a set of unsteady transducers located close to the critical area where the flow separation occurs ie behind the shock.

Figure 7. generic model of the FALCON 7X , *scale 6.25% in the transonic test section*

ETW supports the precise measurement of the following:

- cruise drag, a key factor in kerosene consumption and therefore flying range
- the buffet onset envelope, which defines the airplane's lift limitation and thus an altitude increment, another key parameter for the business jet aircraft (see figure 8, at high angle of attack)
- the pure Reynolds number effects during a typical cruise (see figure 8, at average Cz)

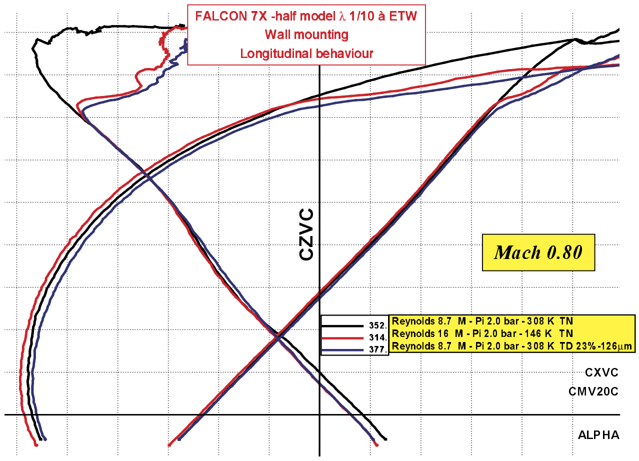

Figure 8. Reynolds effect , *on longitudinal parameters (drag, lift, pitching moment)*

- the effect of the wing aeroelastic deformation on the airplane's longitudinal stability (aerodynamic center, lift slope, induced drag) as shown on figures 9 and 9 bis

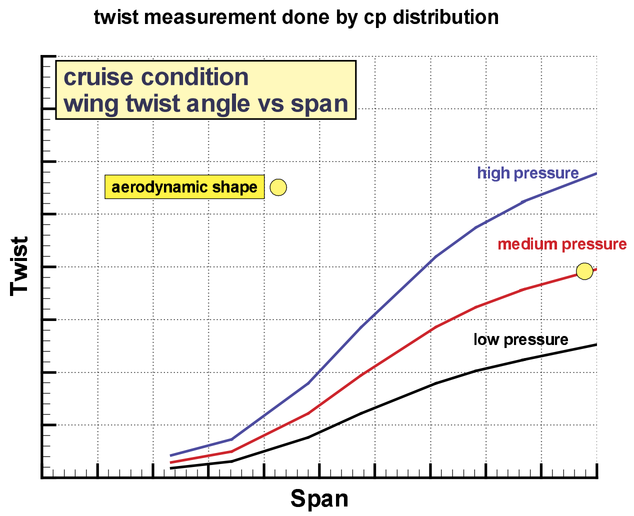

Figure 9. aeroelasticity effect , *on the wing twist angle*

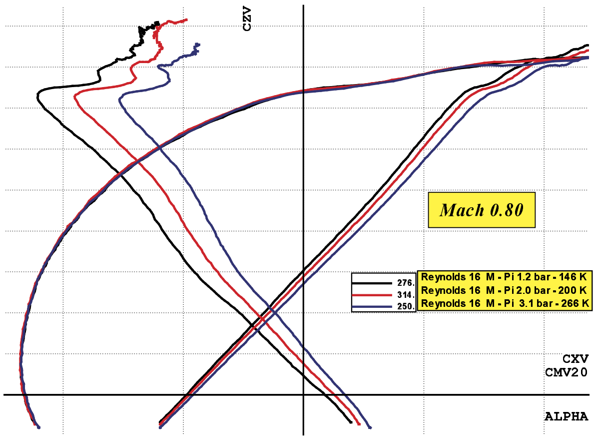

Figure 9 bis. aeroelasticity effect , *on longitudinal parameters (drag, lift, pitching moment)*

- the shape effect and especially the new trailing edge design used on the airfoil

Progress in numerical modelization and experimental techniques are in perfect symbiosis: ETW tests validate our design choices for the new FALCON 7X airfoil and, "in minute detail", the actual precision of calculation results (see figure 10). Without the cryogenic wind tunnel, there would be no way to gauge the trustworthiness or operating limits of numerical models.

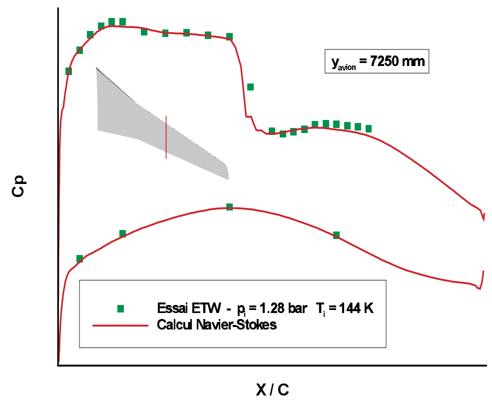

Figure 10. WT/CFD crosscheck , *on typical pressure coefficient distribution along the chord of the wing*

8. conclusion

The ETW results in mid 2002 confirmed the relevance of our new approach. The testing/computation comparison is very good and validates our use of numerical models. Information about performance under real flight conditions improved the procedures and transposition rules for all the traditional wind tunnels used in the full development of the FALCON 7X.

ETW has fullfilled our technical requirement:

- Fine local flow physics analysis by infrared measurements to assess the boundary layer behaviour on the leading edge
- A validation of the tripping devices used in the classical transonic tunnels in order to improve our confidence
- An improvement of our knowledge on the Reynolds number as well as on the aeroelasticity effects to reduce the set of uncertainties
- To select the best configuration due to the reliability as well as a high accuracy of the results