CRYOGENIC MODEL TECHNOLOGY FOR ETW

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1 - ADVANTAGES FOR AN INDUSTRIALIST IN USING AN ETW TYPE WIND TUNNEL

One of an aircraft manufacturer's concerns is to be able to transpose the results obtained in a wind tunnel to flight conditions, in the most reliable way possible.

The cryogenic European Transonic Wind tunnel (ETW) must allow industrial tests to be carried out in conditions which are identical or very similar to the in-flight Reynolds number.

Manufacturers' needs are linked to the prospects of launching new aircraft and new technologies, particularly the laminar concept, together with the new propulsion systems which may be introduced on these new products.

In this context, validation of the ETW must be performed as a preliminary.

Aerospatiale must therefore ensure the quality of the results obtained, and for this purpose acquire know-how in terms of design and development of suitable models, and analysis of the measurements made.

Furthermore, in the ETW industrial phase, Aerospatiale wishes to be able to check out the performances of a given aircraft, taking the effects of motorization into account by implementing engine simulators.

To meet the requirements linked with engine integration, an aircraft manufacturer's main concern as regards aerodynamics is to optimize the effect of engine installation on the wings, and in particular to minimize the level of drag, to obtain the best possible performances of the overall assembly, as from the pre-development phases.

The ETW currently offers aircraft manufacturers the possibility of obtaining the effects of installation in conditions similar to flight conditions (see figure hereafter), together with a data bank for developing calculation codes to be used to assess performances with a high Reynolds number.

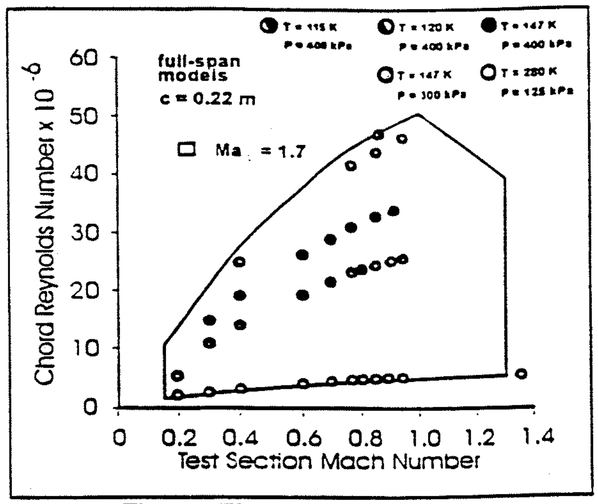


Fig.1 - ETW envelope

2 - FRENCH CIVILIAN PROGRAMME

For the design and development of models for the cryogenic ETW, Aerospatiale and IMFL pooled their skills and resources to draw up and formalize the design and production rules for models to be used in a cryogenic environment, and to apply these rules to the development of specific models with various types of difficulties.

Within the scope of this co-operation between Aerospatiale and IMFL, four phases were identified to meet both the present and future needs of Aerospatiale:

- phase I: technology for high-speed model
- phase II: technology for wing pressure
- phase III: simulation of propulsion
- phase IV: widebody or supersonic ?

The aircraft used for phases I to III is the A340. A brief description of the four phases of the French civilian program is given below.

2.1. Phase 1 Technology for high speed model

The general characteristics of the models are as follows:

Scale: 1:39 (A340-300)

Wingspan: 1.55 m
M.A.C. = 0.1866 m
Fuselage length: 1.61 m
Fuselage diameter 0.144 m

The model is designed to open up the ETW field (Ti = 120 K - Pi 4.5 bar). For the above mentioned conditions, the Reynolds number obtained in the test airflow is 80% that of the A340 flight Reynolds number.
The test mounting are the Z sting and the fin sting.

The model instruments are as follows: internal 6-component balance (ETW property), inclinometer (ETW property), several static pressure tappings to assess the sealing of the model, and a motor-driven horizontal stabilizer remotely controlled throughout the ETW temperature range.

This phase took place from early 1993 to early 1995.

2.2. Phase II - Technology for wing pressure

The model scale is the same as for phase I, i.e. an A340-300 on a scale of 1:39. The model is also designed to open up the full ETW field in terms of total pressure and temperature.

Model instruments are characterized by a high density of static pressure tappings over each half-wing, i.e. approximately 200.

The selected test mounting is the fin sting.

To solve the two-fold problem of static pick-off density and a high total pressure (4.5 bar), technological solutions were developed to overcome the specific difficulties indicated above, to obtain a greater number of measurement pick-offs in areas difficult to access with current techniques, and to ensure a more effective distribution of material, thus resulting in a more globally resistant structure.

This phase began in mid-94 and will be completed at the end of 1996.

2.3. Phase III - Simulation of propulsion

As for phases I and II, the aircraft used for phase III is the A340. The half model is to be developed on a scale of 1:24.

The model and associated engine simulators are designed for use within part of the ETW envelope in cryogenic conditions (Ti = 120 K and Pi = 3 bar), and also in ambient conditions for an S1MA type wind tunnel.

The model instrumentation is as follows: approximately 200 static pressure tappings for the half-wing.
The engine simulator instrumentation is as follows: 30 static pressure pick-offs, 15 thermocouples and 1 accelerometer.

Technological developments are in progress to deal with the above points:

- development of densely honeycombed structures sealed with welded covers, and non cold workable.
- thermal insulation of the engine simulator inflow ducts,
- interface problems between the nacelle and the wings (transfer of stress, simulator power supply etc.)
- technology of the engine simulators in a cryogenic environment

This phase started at the beginning of 1996 and will be completed early in 1998.

2.4 Phase IV - Widebody or supersonic

The aircraft to be used for phase IV will be defined at a later date. This phase will take place between early 1998 and early 2000.

3 - TECHNOLOGICAL CONSTRAINTS ASSOCIATED WITH CRYOGENIC MODELS

The technological constraints we are confronted with when building civilian aircraft models for the ETW concern:

- wind conditions in the airflow, the Mach number, and the stagnation pressure and temperature,
- the possibility offered by the ETW of carrying out wide amplitude scanning of the Reynolds number by varying not only the stagnation pressure but also the temperature,
- lastly, the conditions for intervention on the model between two series of tests, to carry out the required configuration changes, particularly at very low temperatures.

There are therefore four types of constraint:

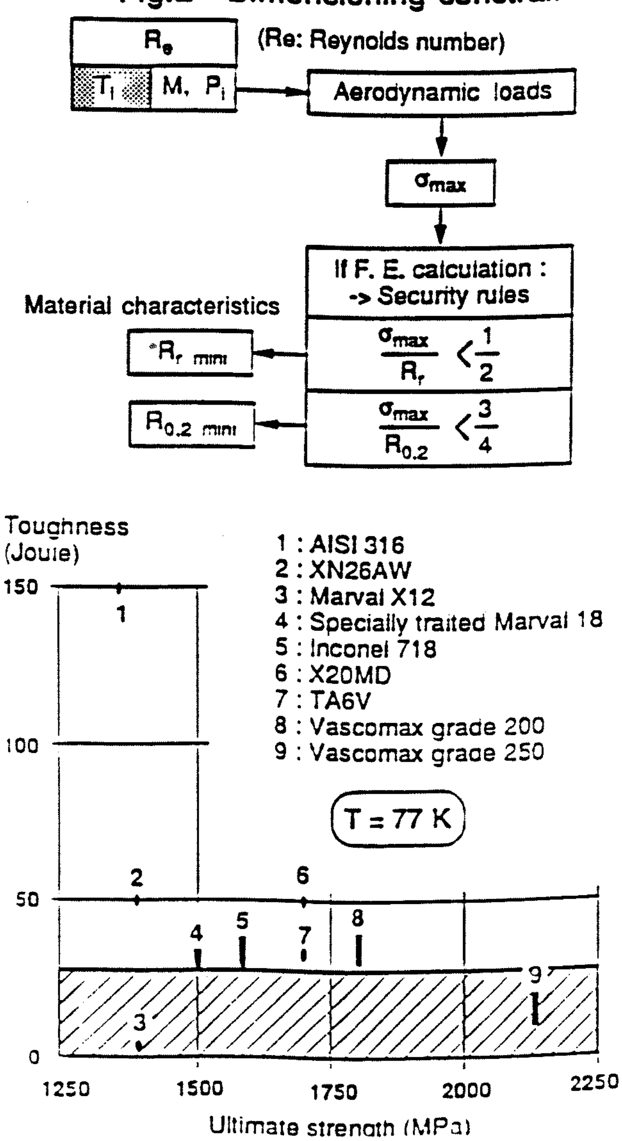
- dimensioning constraints,
- surface condition constraints,
- constraints of thermal origin,
- model intervention constraints.

3.1 Dimensioning constraints

The pursuit of high Reynolds numbers for simulating the real flight conditions of the aircraft, at a given Mach number, simultaneously leads to the lowest possible stagnation temperatures and the highest possible stagnation pressures, given the size of the wind tunnel section. In the specific case of the ETW, this results in stagnation temperatures close to 110K and stagnation pressures of up to 4.5 bar. In these conditions, we can imagine that the models will be heavily loaded, and the sting lines under considerable stress, in some cases up to the practical limits of the flight envelope accessible in wind tunnels.

The structural constraints, which depend only on the Mach number in the airflow and the stagnation pressure, will be highest when the ambient temperature is close to 110 K. In these temperature conditions, only aluminium and titanium alloys, stainless steels, steels with a high nickel content such as maragings and, even more so, Inconel, are suitable.

Fig.2 - Dimensioning constraints



Nevertheless, depending on the ultimate strength required, we must make sure that these materials are not too fragile and do not lead to an explosive fracture.

A practical lower limit for the toughness of the materials has been set by the ETW at 30 joules (Kv on standard 10 x 10 mm2 test sample). Figure 2 shows the current alloys used to produce models for cryogenic wind tunnels. Note that beyond a tensile strength of 1500 Mpa, the alloys have a resilience of between 50 and 30 joules, and more often between 40 and 30 joules, or even less.

At this level, there is practically no plasticity and special attention must be given to the design drawing as regards joints, cutouts etc. to avoid areas of sudden variations in stress where cracks could form and lead to an explosive fracture.
From a practical viewpoint, our choice will be limited to AISI 316, Marval 18, maraging steels specially treated at 1500 Mpa, grade 200 Vascomax and titanium alloys.

Given the level of structural constraints encountered and the ductility of the materials used, it is generally essential to dimension the model structures and the sting line by a finite element calculation. As the "jig" form of the model must be determined with a high degree of accuracy (so that in a given point in flight, the deformed shape of the model is identical to that of the aircraft), and as this may only be defined from a finite element calculation, only an additional meshing load is required to obtain the constraints.

Taking the dynamic oscillation constraint into account, due to the flexibility of the sting line, the practical rules are then:

- σ max.< mini (0,5 * R_r ; 0,75 * $R_{0,2}$)
(R_r: ultimate strength) ($R_{0,2}$: yield limit)

3.2 Surface condition constraints

The pursuit of a surface condition which does not interfere with the thickness of the boundary layer, as a function of the Reynolds number, and given the high values of this number, results in surface conditions which are particularly immaculate but which may be attained by manual "mirror" polishing. Common mean roughness values are 0.3 µm. These values may still be measured by conventional contact roughness meters. The change to be made to the surface condition according to the Reynolds number is given in figure 3. It may be noted immediately that the finishing effort will have nothing in common with a conventional model for a non-cryogenic wind tunnel, where the Reynolds numbers are limited to around 15 millions.

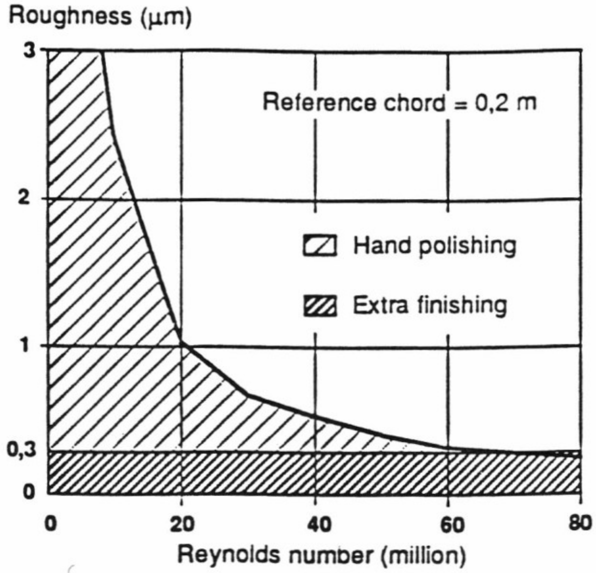


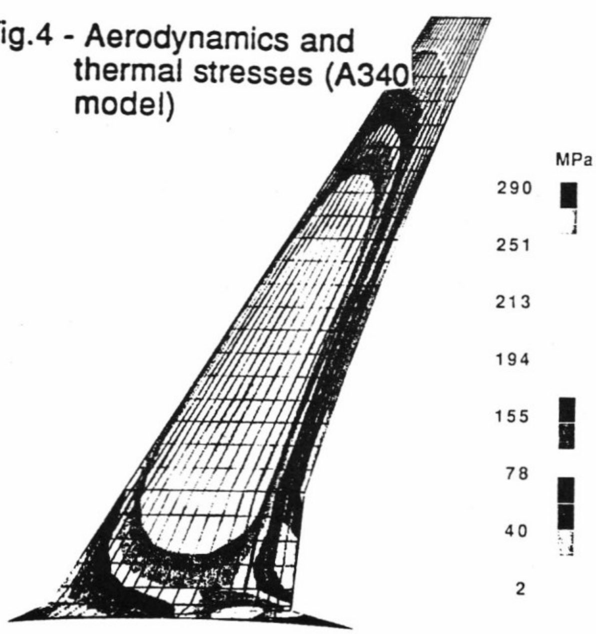
Fig.3 - Roughness versus Reynolds

3.3. Constraints of thermal origin

These constraints appear when there is a rapid change in the stagnation temperature of 24 K/min. or when the model is placed cold in the airflow. Calculation of these stresses is complex, as the convection coefficients in the presence of the boundary layer must be determined beforehand.

As a general rule, these thermal stresses have only a limited effect on the mechanical resistance of the model elements. On the other hand, in the fuselage-balance attachment or in the balance-sting attachment area, which is heavily loaded and where there is localized overstress due to factors of shape, the effect of these stresses is certainly not to be overlooked. Calculation is still necessary. As an example, figure 4 shows the result of a complete aerodynamic and thermal calculation on the wings of the A340 aircraft model in the ETW.

Fig.4 - Aerodynamics and thermal stresses (A340 model)



3.4. Intervention constraints

Intervention constraints exist when the model has to be modified at cryogenic temperatures. When the model is in position on its sting line, it is out of the question, simply for reasons of time, to reheat the assembly, work on the model, and then return to the cryogenic temperature before replacing it in the airflow.

To overcome this difficulty, ETW offers users a respirable dry air cold room at -60°C, where the model, in an open chamber, is in a dry airflow which may go down to -150°C. Figure 5 shows a skeleton diagram of this room. For such cold conditions, the operator must wear gloves and an isothermal suit. This considerably impairs his dexterity, and removal-reassembly operations must be kept to a minimum. Similarly, the time spent in this hostile environment for such operations must be minimized.

A special effort must therefore be made in designing the assemblies, and in the use of motor-driven actuators wherever possible.

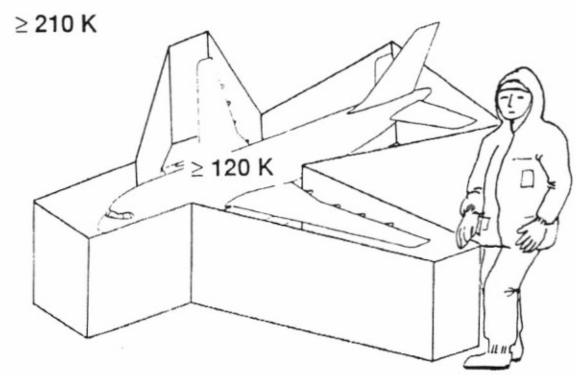


Fig.5 - Intervention constraints for the tests at ETW

4 - SPECIFIC TECHNOLOGICAL DEVELOPMENTS

The techniques presented are implemented as part of the exploratory technological development of cryogenic models for use in the ETW, concerning the Airbus A340 aircraft.

Four separate developments are described:

- cam assemblies,
- motorization of the horizontal stabilizers,
- "multilayer" technology for wings equipped with a large number of pressure tappings,
- TPS technology (Turbine powered simulator).

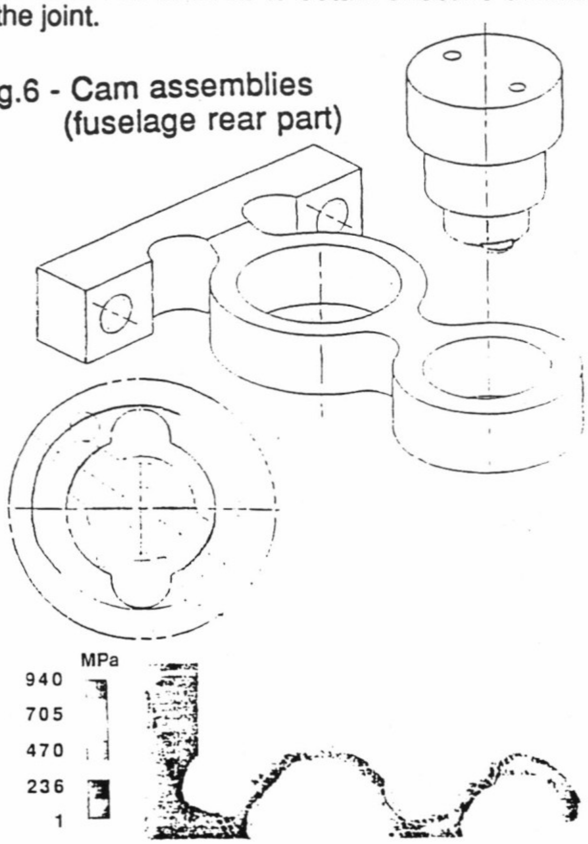
4.1 Cam assemblies

These assemblies were designed to fulfil two functions: to offer deformation continuity (embedding) and to allow quick installation and removal using the "quarter turn" process with a stud-guided wrench to prevent slippage onto the remainder of the structure.

To comply with these conditions, the assembly will therefore be pre-stressed, by acting on the elastic peening force between the faces of the connecting parts in contact. As long as this peening force exists, in fact, the faces in contact cannot be separated, and deformation continuity between the connected parts is thus achieved.
The second point is to perform "quarter turn" assembly by introducing a cam which fulfils two functions, pre-stressing and reversible locking.

Pre-stressing is easily achieved via a spring structure, shown in figure 6, placed under stress by the elastic deformation imposed by the cam. A finite element calculation must be carried out for this structure to supply the peening force imposed by the continuity of the joint and to distribute the internal stress such as to obtain effective elasticity of the joint.

Fig.6 - Cam assemblies (fuselage rear part)



The cam is shaped in such a way that the application force reaches a maximum during its rotation, and is then slightly reduced at the stagnation point. In this case, if this reduction is correctly estimated, the cam remains locked in position even under the effect of the oscillation forces applied to the joint. Furthermore, the constraints in the spring are always less than those initially introduced upon tightening, as the application strain between the faces of the joint can only diminish.

The cam is also held fore and aft by an elastic locking device, and its installation is completely repetitive, allowing for a perfect fit on the skin surface.

This is the principle, shown in figure 7, on which the rear fuselage attachment of the A340 "high speed" model was based. Note the excellent continuity between the fuselage elements, and the complete discretion of the cams. Installability-removability at the temperature of liquid nitrogen was demonstrated and validated.

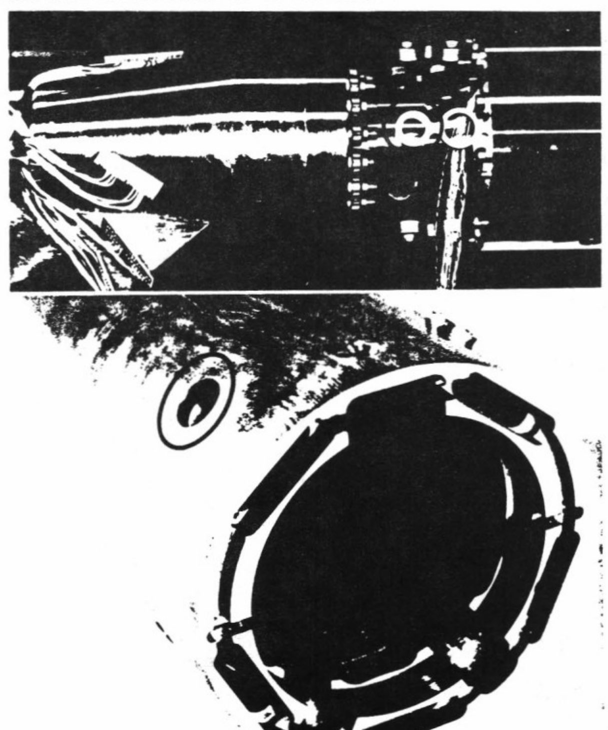


Fig.7 - Cam assemblies (photos)

4.2 Motorization of the horizontal stabilizers

To avoid manual adjustment of the horizontal stabilizers, a cryogenic environment motorization was developed along the following principles:

- ballscrew drive and electrical brake to ensure the irreversibility of the system, given the range of loads applied,

- use of a step motor,
- rotation axis on dry lubricated bearings by the projection of microparticles of molybdenum disulphide and hot curing.
- use of standard off-the-shelf elements requiring limited adaptation for use in a cryogenic environment.

A Sonceboz step by step motor was chosen, with a position holding torque of approximately 1 mN, which, given the chosen reduction, is sufficient to ensure the irreversibility of the drive system.

Cryogenic adaptation consists in readjusting all the standard elements of this motor, cleaning them thoroughly and, in some cases, dry lubricating them by molybdenum disulphide curing. Once reassembled, the motor must be free of all traces of humidity, grease or oil. It must be kept in a completely dry atmosphere.

The ballscrew is made by Transroll, in maraging steel, and is also thoroughly cleaned and dry lubricated.

The bearings consist of dry friction bushes, with a functional elastic fit.

Figure 8 shows all the parts composing the rear part of the A340 aircraft "high speed" model for the ETW.

This motorization is satisfactory provided if there are no traces of humidity or pollutants in the overall mechanical drive system of the horizontal stabilizers. The "habits" of the mechanics must be resisted, consisting in oiling rotating parts or failing to remove traces of cutting oils encountered, particularly in tapping or drilling operations.

Fig.8 - A340 model rear part (general view)

The molybdenum disulphide treatment considerably improves the friction characteristics of the assemblies, but provides no guarantee against the risks of sticking in the presence of humidity. It is imperative for residual humidity to be removed by nitrogen or helium gas drying.

A definite improvement is observed in the characteristics of the motor, particularly the static torque at low temperatures. The gain is approximately 25% at the temperature of liquid nitrogen. Similarly, assisted by the reduced functional clearances, the positioning accuracy and its repeatability increases at low temperatures. We thus achieve a positioning accuracy of the horizontal stabilizer assembly of 0.01° for the overall system, as in figure 9.

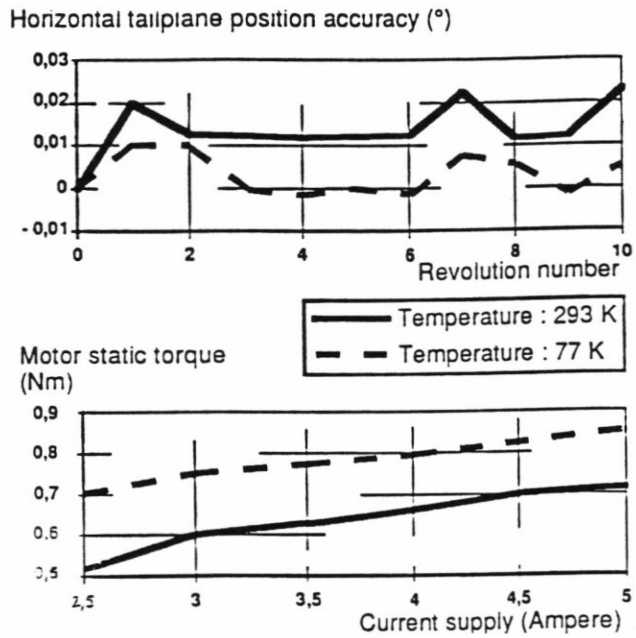


Fig.9 - Characteristics of the HTP motorization

4.3 Multilayer design of the wing structures for models equipped with a large number of pressure pick-ups

This technique was devised several years ago to solve the problem of developing, in a cryogenic environment, small profiles with a large number of static pressure pick-ups, while maintaining a one-piece structure of very great purity and a high level of profile accuracy.

As it was practically impossible to produce a hollow structure sufficiently rigid and mechanically resistant, it was proposed to follow the example of multilayer printed circuits by designing a metallic multilayer. The profile structure, which is generally two-dimensional, was therefore composed of an assembly of metal sheets bonded together by brazing or diffusion.

The same idea was used for the wings of the A340 "Kp" model for the ETW. Diffusion techniques for the assembly of titanium alloys have considerably evolved these past few years, and the industrial resources implemented, composed of high temperature, high-pressure large-scale presses in an inertial gas, as in figure 10, can now be used for model-size structures. Furthermore, the assemblies produced by this method have almost the same mechanical characteristics as the basic alloy, particularly as regards shear strength and fatigue behaviour.

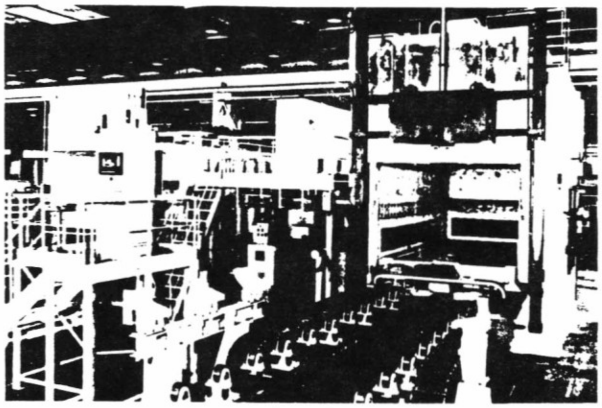


Fig.10 - View of the pressing-machine

The wings are therefore designed as a stack of metal sheets of constant thickness in TA6V, each sheet having its specific network of pressure channels produced mechanically on a digital control milling machine. Routing is designed using software adapted from routing software for electronic multilayer circuits. Figure 11 shows an example of routing. Communication between the sheets, for the readjustment of certain channels, is provided by cross shafts.

The assembly thus formed was fatigue tested under three-point deflection at ambient temperature and at 120 K, as in figure 12.
Behaviour is satisfactory, but there is nevertheless a cracking tendency along the edges of the channels, as in figure 13, although this does not lead to destruction or to intercommunication between channels, even when 0.7 mm apart. This point must be monitored, however, and may result either in limiting the life of the model to a few hundred hours, or in the surveillance and follow-up of the fatigue cycles effectively undergone by the structure. The wing feed-through connection with the pressure gas tubes leading to the scanivalves is provided by bonded steel end fittings, figure 14.

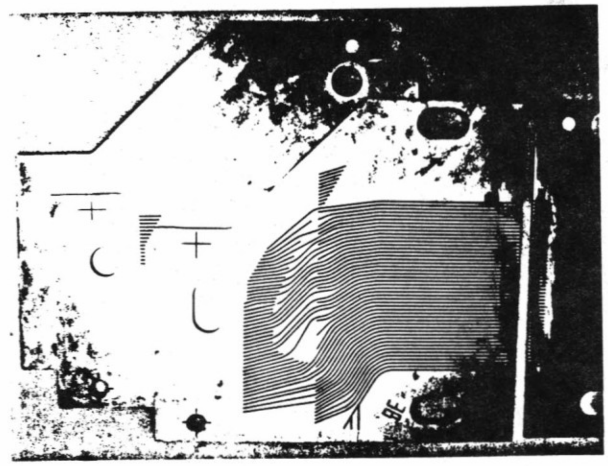
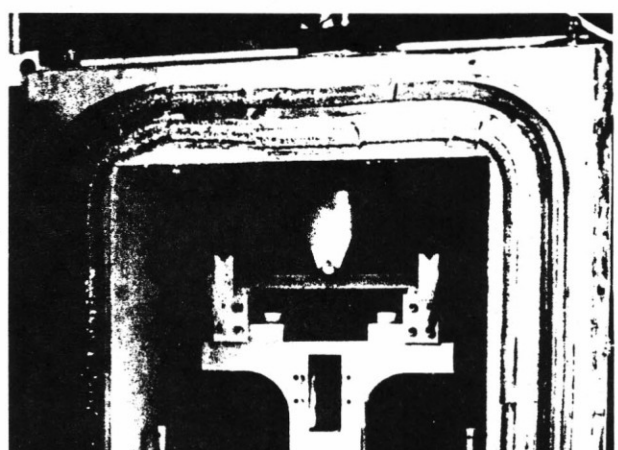


Fig.11 - Example of routing (multilayer wing)

Fig.12 -

Fatigue test under three-point deflection (cryogenic enclosure)



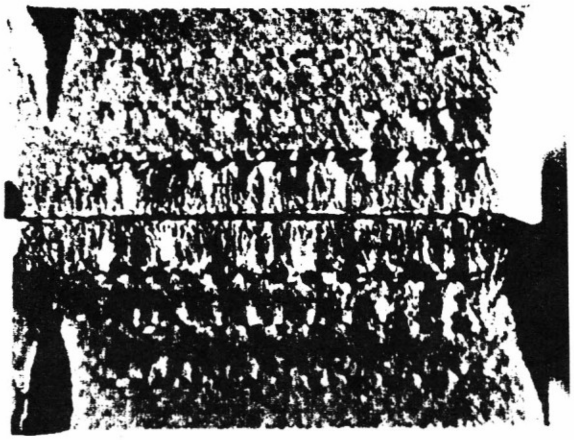
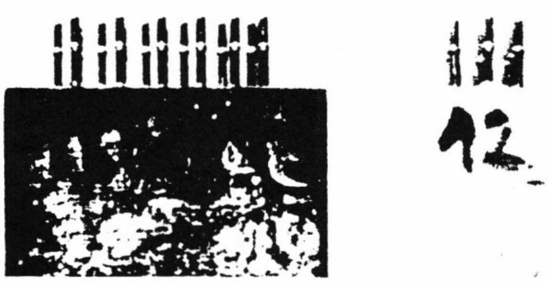


Fig.13 - View of two kinds of crakings (four layers sample of TA6V)

Fig.14 - View of connection pipes (four layers sample of TA6V)



4.4 TPS technology (Turbine Powered Simulator)

The aim of motor driven tests in a wind tunnel is to determine the aerodynamic performances of an aircraft, taking the jet effect of the engines into account. Motorization on the model is simulated by engine simulators which represent the intake and jet of the real engine as faithfully as possible (similarities between the fan compression ratio and the corrected fan mass flowrate). The motor-driven nacelles are first calibrated, to determine their thrust for different operating engine speeds. Once these calibration laws have been drawn up, they serve to correct the engine simulator thrust measurements carried out on the model in the wind tunnel, as this is very different to the thrust of the real engine. The performances of the aircraft may thus be determined, taking jet interference into account.

Tests on motor-driven models in a cryogenic environment involve specific technical developments, particularly for the engine simulators.

The simulator will be designed for:

- a fan compression ratio = 1.65:
- a corrected fan mass flowrate = 0.7 kg/s

It must operate in both cryogenic conditions (3 bar/120 K) and ambient temperature and pressure conditions.

The first key point in designing this type of simulator is the choice of the bearing technology, which rotates the fan+shaft+turbine assembly.

The following roller bearing technologies were rejected:

• bearings with oil lubrication:
- risk of polluting the wind tunnel airflow with oil rejects
- very difficult, if not impossible, to fill the simulator oil tanks between two tests

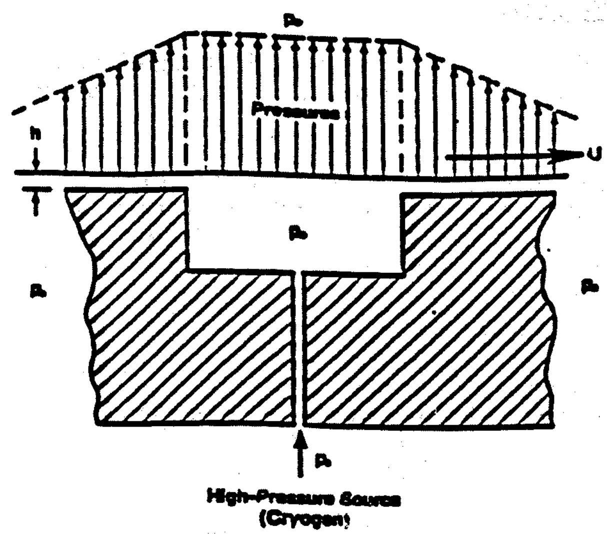
• bearings with grease lubrication
- bearings require thermal insulation
- maximum speed too low

• ceramic ball bearings
- life too short.

Three other types of technology were considered:

• aerostatic bearings
• foil bearings
• magnetic bearings

An aerostatic bearing uses an external pressure source to establish a field of pressure between the stator and the rotor. This technique can be applied to both radial bearings and axial thrust bearings.



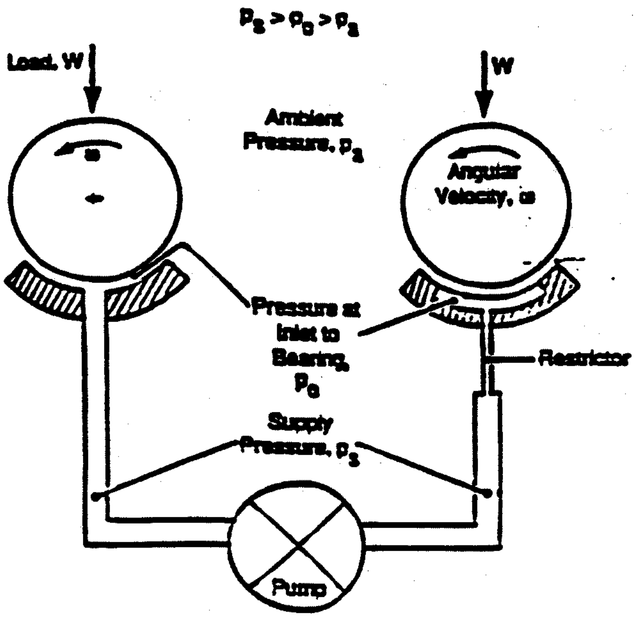


Fig. 15 - Radial aerostatic bearings

A foil bearing is a hydrodynamic gas bearing capable of supporting a radial load (journal bearing) or axial load (thrust bearing). The lift effect is obtained by the relative speed between the fixed and mobile faces, which creates a thin film of gas under pressure. Foil bearings have the following advantages and drawbacks:

Advantages:
- limited size,
- absence of wiring and instruments;

Drawbacks:
- loads associated with external pressure and temperature conditions,
- starting friction.

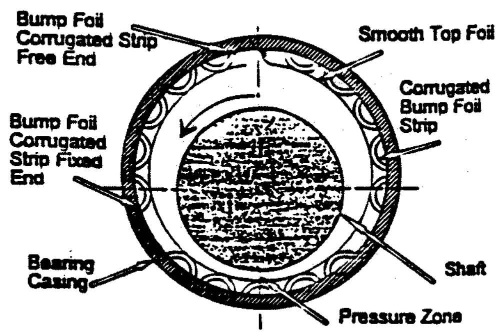


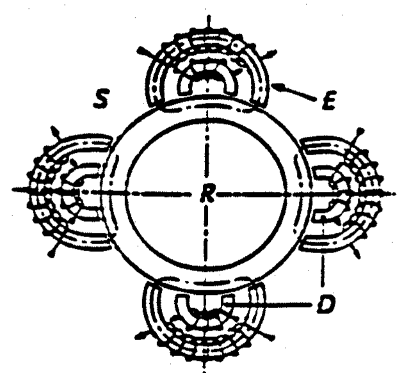
Fig. 16 - Journal foil bearing

Magnetic bearings lift a rotating shaft by the action of magnetic forces in all three directions in space. A magnetic bearing may be passive and/or active. It is passive if it is not composed of permanent magnets, and active if it is composed of electro-magnets. The position of the rotor in space is actively controlled by sensor and inductor circuits.

Magnetic bearings have the following advantages and drawbacks:

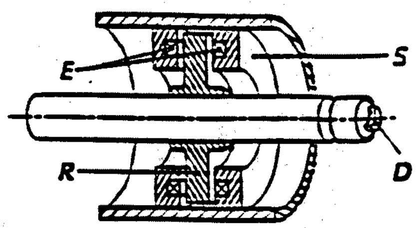
Advantages:
- shaft rotation in the absence of any contact
- high degree of reliability,
- insensitive to external pressure and temperature conditions,

Drawbacks:
- voluminous
- considerable amount of wiring and instruments
- risk of interference to aerodynamic measurements



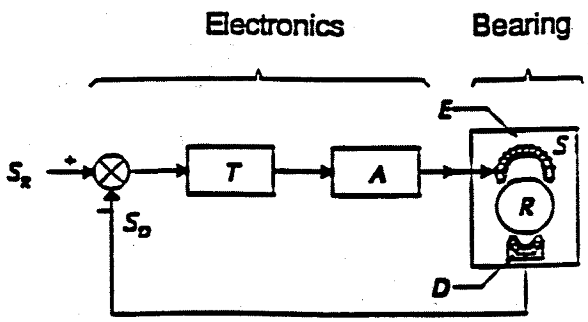
D sensor R rotor
E electro-magnet S stator

Fig. 17 - Radial bearing



D	sensor	R	rotor
E	electro-magnet	S	stator

Fig. 18 - Axial thrust bearing



A	power amplifier	S	stator
D	position sensor	So	sensor signal
R	rotor	Sr	reference signal
E	electro-magnet	T	signal processing

Fig. 19 - Electronic servo-system

Two of these three types of technology can be developed for our cryogenic engine simulator:
- magnetic bearing technology
- foil bearing technology.

Two feasibility studies are being conducted, and once these are completed the final decision will be made as to the most suitable technology.

5 - ETW TESTS:

For us, these tests at ETW were the most effective means of becoming acquainted with the wind tunnel.

A global approach was made within the major Airbus partners, with the result that Aerospatiale uses an A340 model, BAe an A320 model and DBAA an A310 model, with each partner in control of its tests but giving the other members the benefit of its experience.

Aerospatiale, therefore, with the help of ONERA IMFL, developed a new design model complying with cryogenic constraints, taking an A340-300 on a scale of 1:39 as basis, corresponding to phase I.

The test programme was an ambitious one for an initial campaign, and fairly extensive with respect to the number of polars to be carried out.

The major objectives were:

- to highlight the effects of the Reynolds number on the general aerodynamic characteristics;
- to identify and quantify the effective capabilities of this new wind tunnel;
- and, of course, to validate the studies and design choices of the model.

To do this, we wrote a test programme build around a grid taking the aircraft cruising point as target, and highlighting:

- the Mach number variations from 0.3 to 0.86;
- the effects of the Reynolds number from 4.10^6 (for comparison with test results from traditional wind tunnels) to the maximum achievable value 33.10^6 (for comparison with in-flight measurements);
- the effects of dynamic pressure at constant Mach and Reynolds numbers, to validate the wing flexibility effect.

Convinced that in this type of wind tunnel it is not necessary to trigger the boundary layer transition (the higher the Reynolds number for the test, the more this necessity may be questioned), Aerospatiale devoted a large part of the programme to determine the position of the natural transition on the airfoil surfaces.
For this reason the test programme was divided into two parts, with each part based on the same test grid, and therefore carried out in the same conditions.

The aim of the first part is to quantify the effects of the Reynolds number on the longitudinal aerodynamic coefficients up to the buffeting limits, and to take advantage of these incidence excursions to observe and record the transition positions on the different surfaces, using an infra-red camera.

The model is assembled on a Z sting.

The second part of the programme is devoted to measuring the fine drag, using the exact position of the boundary layer transition (analysis of the infra-red images) to carry out friction corrections.
In this case, the model is held in the airflow by a so called fin sting.

The model configuration can be the fuselage alone, fuselage + wings, fuselage + wings + nacelle, or the complete aircraft. For this last configuration, the model is fitted with a motor-driven horizontal stabilizer to avoid tedious comings and goings between the test section and the quick change room to the model to modify the adjustments.

In March 95, we therefore began tests with the first part of the programme.
In addition to the normal difficulties encountered with the first installation of a new model in a new wind tunnel with teams not yet fully acquainted with each other, we encountered difficulties in implementing the infra-red displays, together with problems in handling the horizontal stabilizer.

Two types of problems were encountered as regards the infra-red camera display technique.
The layer of insulating paint on the model was thin to be as discrete as possible and to avoid disturbing the measurements of the balance. Because of this, the conduction phenomena through the model elements were relatively significant, notably reducing the contrast of the infra-red displays.
In addition, the capabilities of the infra-red camera used (conventional infra-red camera) deteriorated very rapidly with the drop in temperature of the airflow, until around 200K when no further displays were obtained.
As one of the aims of this test campaign was to observe the position of the boundary layer transition, we restricted the test to the range of temperatures fully accessible to the camera, i.e. ambient temperature (- 293 K). However, temperature excursions were made down to 205 K to identify the limits of display with this type of conventional infra-red camera.

On the model itself, we encountered a few problems with the motor of the horizontal stabilizer.
No doubt due to overheating at the beginning of the test campaign, the effective torque of the motor was reduced by half, making it difficult to move the loaded stabilizer and its servo-control to the required value (although this had been tested during the model qualification tests, with the stabilizer loaded with simulation of aerodynamic forces). However, this did not jeopardize the execution of our tests.

This phenomenon was amplified by the fact that we were unable to use the static retaining current in the motor, as this was intermittent, causing considerable interference to the balance measurements.

These causes of faulty operation were identified, and a new motor has since been installed in the model.

6 - CONCLUSIONS - SUMMARY:

An industrial approach was adopted for this initial contact with the ETW and its personnel. Despite a few teething problems to start with, the overall results are positive.

Positive for the wind tunnel, as its considerable potential was revealed in the quality of its airflow, and also in the processing of the information recorded.

Positive for the balance and the model equipments.

Positive for the model, as despite the problem with the motor (since solved), its dynamic behaviour was very satisfactory and progressive, even in buffeting areas.

Positive for our team, which was able to fully benefit from its experience with the wind tunnel, and in the approach to be adopted from both a practical and theoretical viewpoint.