FLYING THE MIRAGE 2000 BY WIRE

by Jean COUREAU ex-project pilot of the MIRAGE 2000

Persons who do not know the DASSAULT-BREGUET firm well, may have been surprised to learn of their producing a fly-by-wire aircraft. As for us, test pilots of the Firm, this only consitutes a stage - certainly important but normal on the permanent evolution of our aircrafts.

Indeed, as early as 1959, MIRAGE IV pilots have operated their aircraft flight controls in normal modes through electric signals only (see fig. 1).

At that time and in case of Electrical Flying Control System (EFCS) failure, a mechanical linkage could take over through disengage bell-cranks ; this safety arrangement allowed to operate with one electrical channel only.

On that same type aircraft, an electrical gain arrangement adjusted the pilot force law to prevailing flying conditions. As for the auto-pilot, it issued electrical signals directly to the electro-hydraulic servo-controls.

FLY BY WIRE AND C.C.V. DEVELOPMENT fig 1

1957 :	SECONDARY ELECTRICAL FLIGHT CONTROL DEVICE (DAMPER)	— MIRAGE III
1958 :	ELECTRO-HYDRAULIC POWER SERVO-CONTROLS (WITH DISENGAGEMENT BELL-CRANK)	— MIRAGE IV
1962 :	TRIPLEX SELF-MONITORED FLIGHT CONTROLS (MECHANICAL BACK-UP)	— BALZAC V MIRAGE III V
1967 :	FLY-BY-WIRE ON ROLL AXIS (V.G.)	— MIRAGE G 01 MIRAGE G 8
1973 :	TRANSVERSAL GUST ALLEVIATION	— MERCURE
1974 :	FLY-BY-WIRE SYSTEM FOR STABLE A/C (MECHANICAL BACK-UP ON PITCH AXIS)	— (MIRAGE G 8 A)
1978 :	DIRECT FORCE MODES (PURELY DIGITAL)	— FALCON 20 R
1978 :	FLY-BY-WIRE AND C.C.V. FOR UNSTABLE A/C (WITHOUT MECHANICAL BACK-UP)	— MIRAGE 2000 SUPER MIRAGE 4000

As you can see, the EFCS is therefore not new to us.

Few aircraft manufacturers are lucky enough to run their own "Equipment Department", developing and producing electrical or mechanical flight controls for all the aircraft they make.

Figure n° 1 shows the evolution of our flight control concept.

It will be observed that the control covered by EFCS constantly increases, as more computing channels become available but our main objective still remains the safety of operation.

After the MIRAGE IV, where the electrical control was primarily giving the aircraft a good damping, VTOL machines required more complex relations between pilot controls displacement and corresponding flight controls response travel. At that time, accelerometric and gyrometric signals already completed or replaced pilot orders, especially in the stationary phases of the flight.

Variable geometry wing aircraft also imposed a purely electronic solution for spoilers control (roll axis) ; in fact, this control was the first electrical one not doubled up by a mechanical linkage and operated since 1967. It will be noted that roll control was partially achieved by differential displacement of the horizontal tail surfaces (tailerons), also electrically controlled but including a mechanical back-up arrangement.

In 1974, modern design of electrical flight control integrating gyrometric, accelerometric, aerodynamic and even trajectory (angle of attack) information, came as the solution for the G 8A or SUPER MIRAGE project.

At the time though, the aircraft was yet made to remain in stable conditions, for a mechanical linkage still remained as ultimate back up.

Research for a better performance, especially in combat, made designers contemplate flying in instable conditions but, at the same time, they experienced qualms of conscience over a decision leading to abandon the mechanical linkage back-up arrangement for the benefit of the all-electrical control.

Many had to be convinced - with the pilots much less so - that a flight control system including three to four purely electrical and completely independent control channels, was more reliable than the old mechanical control linkage.

Statistics proved right against feelings and passion gave way to "objectiveness" but still remained slightly "measured", as proved by the MIRAGE 2000 prototype which retained a mechanical back-up control linkage for a few months.

ADVANTAGES OF ELECTRICAL FLIGHT CONTROLS

I hope that all members of the assistance who know this problem very well, will forgive me for recalling here all main points in favor of EFCS :

Improvements brought about in flight characteristics, allow flying the aircraft in longitudinal instability conditions, where "normal" flying would just not be possible.

The gain in performance comes from a reduction in drag due to the pitch control surface deflection. When this control is of conventional type, gain at cruising speed is small and only becomes significant in manoeuvres or in approach.

On a delta wing aircraft, the gain is considerable and allows rehabilitating this formula by cancellation of its main draw-back which is heavy drag at high angles of attack. Attractiveness of the delta wing plane then comes back in force : low wing loading, large internal space, structural rigidity, clean flight behaviour, super-sonic drag etc... and AMD-BA is no longer alone to feel that way.

MIRAGE 2000

fig 2

ELECTRICAL FLIGHT CONTROL SYSTEM

MAIN OBJECTIVES

- CONTROL OF AN UNSTABLE AIRCRAFT
- CONTROL OF THE CONFIGURATION (LEADING EDGE SLATS,..)
- IMPROVEMENT OF OPERATIONAL EFFICIENCY
  - IMPROVEMENT OF FLIGHT CHARACTERISTICS
  - CONTROL OF AIRCRAFT IN HIGH ANGLE OF ATTACK CONDITIONS
  - AUTOMATIC OPERATING LIMITATIONS (vs. AoA, LOAD FACTOR,...)
- IMPROVEMENT IN SAFETY
- IMPROVEMENT IN MAINTENANCE
- WEIGHT REDUCTION

Other advantages remain possible : absence of concern over pitch and roll axes control, allowing the use of leading edge slats, particularly increasing aspect ratio in combat manoeuvres.

Finally, the usual flying characteristics degrading experienced when carrying external stores, now becomes a thing of the past : most varied type loads are henceforth acceptable.

All above stressed points no doubt make pilots happy but what makes them "fall in love" with this system is the complete change found in the flying characteristics, the union of stability and manoeuvrability, and a perfect mastering of the flight offered by the EFCS.

The way we succeeded in practically relieving the pilot from the usual burden to watch aircraft manoeuvre and structure limits, and thereby give him a maximum operational efficiency, will be studied further.

Let us see now how the system is designed.

MIRAGE 2000 ELECTRICAL FLIGHT CONTROLS

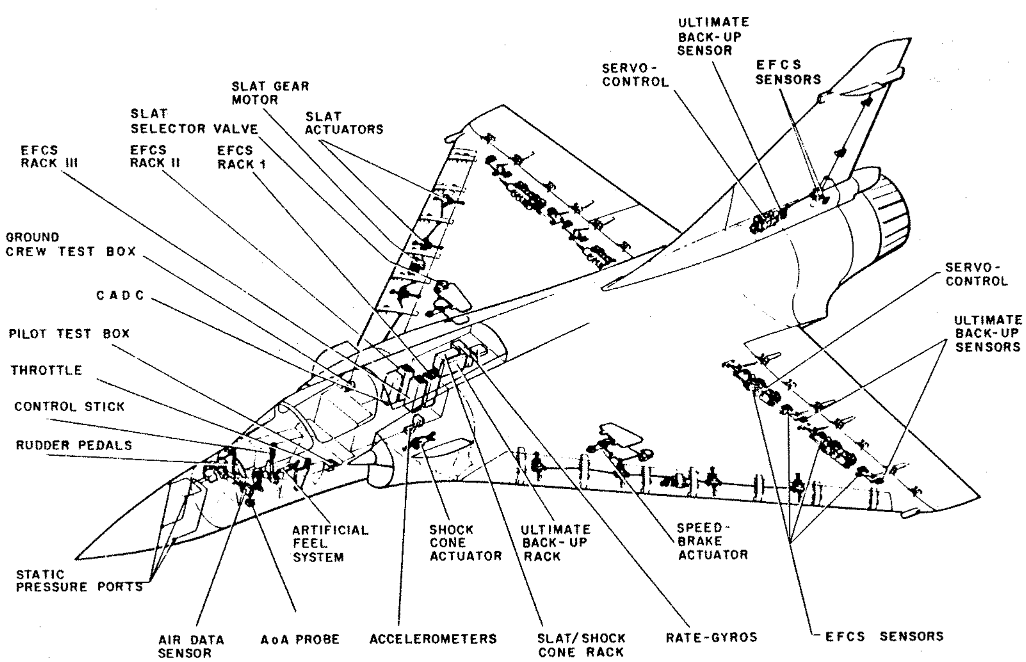
General lay-out (Fig. 3). Design simplicity of the delta wing is clearly displayed here : the four elevons extend over the whole wing trailing edge and are controlled by four dual-body electro-hydraulic servo-actuators. The rudder is similarly controlled by one dual-body servo actuator.

What is new on this delta wing is the automatic EFCS monitoring control of the leadind edge slats, these slats being operated by hydraulically driven screw actuators.

MIRAGE 2000

fig 3

FLIGHT CONTROL SYSTEM



MAIN DESIGN PRINCIPLES OF THE CONTROLS

- Two separate hydraulic systems, which proved their full reliability over thirty years on our aircrafts, (Fig. 4)

fig 4

MIRAGE 2000

FLIGHT CONTROL SYSTEM REDUNDANCIES

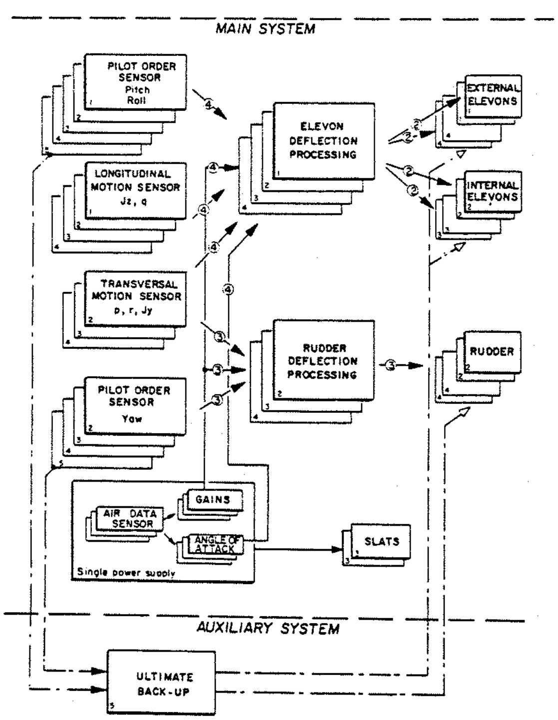
* HYDRAULIC POWER	• 2 HYDRAULIC SYSTEMS (+ ELECTRO-PUMP)
* ELECTRIC POWER	• 4 ELECTRIC SYSTEMS
* SENSORS	• 3 or 4 (DEPENDING ON FUNCTION)
* PROCESSING	• ADAPTED TO FUNCTION AND CHANNEL • 4 (PITCH / ROLL CHANNEL ...) • 3 (YAW CHANNEL ...) • 2 (LEADING EDGE SLATS CONTROL ...) • RE-CONFIGURATION OF PROCESSING DEPENDING ON THE SYSTEM INTEGRITY

- Four completely independent electrical power sources,

- Quadruplicated or triplicated sensors, according to need,

FLY-BY-WIRE CONTROL SYSTEM REDUNDANCIES

fig 5



- Computers : their number depends upon the number of functions to be covered :

  . four, for pitch and roll axis control,

  . three, for yaw axes control,

  . two, for the wing slats.

Internal connections arrangement is directly related to the system hybrid design : analogue processing in each channel, comparison and digital active selection, digital gains and analogue input on servo-controls.

A flight processing channel called "ultimate back-up" allows survival in very adverse conditions.

Technically enquiring minds will find more details in another diagram (fig. 6)

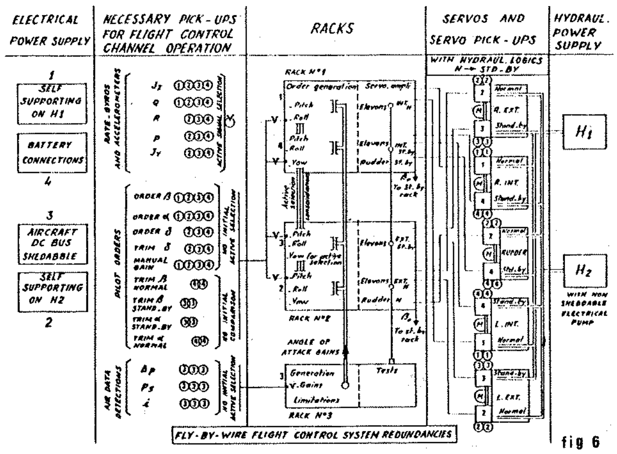


fig 6

FLYING CHARACTERISTICS ACHIEVED

PRELIMINARY ADJUSTEMENTS

AMD-BA specialists managed to work-out a highly sophisticated computation centre for preliminary flight system developments. Working from data obtained through various wind tunnel tests, a specialized team of highly skilled engineers studied the aircraft anticipated behaviour and, therefrom, determines flying laws to be applied. In order to make this theoretical approach of the problem an efficient one, reading in tea leaves or out of a crystall ball is useless and only a long experience in exhaustive link-work between wind tunnel and flight tests, can be relied upon.

The "Flight Characteristics" team has been "learning" for more than twenty years, to record the differences - even the smallest ones - existing between anticipations and tests ; they also learned to correct the existing aircraft, to finally make the necessary corresponding provisions on machines to come.

One must really see it to believe how this head team studies most minute details, when preparing flying laws of a new aircraft !

When its job is done and the team feels ready, it invites pilots to evaluate results of its calculations in a simulation cockpit of very simple looks and not carrying costly equipment but connected to a full size flight control test bench and to a very powerful computing centre.

Then, the spell operates and pilots "sample" simulated aircraft reactions while becoming acquainted to the new bird.

The whole electronic flight control system is framed up into separate units which, after going through a last simulation bench check, are fitted in the aircraft.

The account I just presented perfectly explains the "near-automatic" success in flight characteristics met by our planes on their maiden flight. In fact, AMD-BA pilots drift into "wrong habits" : they only have minute adjustments to make and do not fear errors in flying aid systems principle.

As one can guess, use of this "miracle medicine" with the MIRAGE 2000, produced excellent results.

I had the honour to fly the prototype on its maiden flight on March 10th, 1978 : for a pilot, such an experience is unforgetable. To feel a "rock stable" aircraft as soon as she is airborne is already pleasant, but discover that the slightest pressure on the controls is immediately followed by a move with a precision so far unknown, fills you all with satisfaction.

The new flight controls really wipe out transonic and super-sonic peculiarities and no new change appears within the whole flight envelope. Low speed test then, showed a tremendous improvement in flying characteristics : the age-old delta wing handling work-load has vanished ! The aircraft gently follows changes in glide path, maintains newly set attitudes and does not "run away" from the hands of the pilot who can then concentrate on the thrust. So good was that final leg that when debriefing, we could not help making a comparison with handling of a push-bike whose "approach" characteristics are known the world-over.

The following flights brought to light many other improvements such as the perfect cross-coupling which allows full aileron action in combat, even at very low speed : flying at 120/130 kt. with full back stick throughout, the pilot can apply full aileron on one side then full aileron again on the opposite side. For many other aircraft, this is a sure way to enter a spin but with the MIRAGE 2000, a glance at the "ball" shows a surprisingly modest move.

Success is now complete and electrical flight controls are held in high esteem by all pilots who have the pleasure to try them ... Of all new devices displayed by the MIRAGE 2000, the EFCS is found the best, by far.

Very quickly, one gets used to the automatic angle of attack limiting system and the fighter pilot in action is freed from the major concern of watching the approach of manoeuvre limits with the fear of possibly losing control.

AND HERE WE START AGAIN ...

Once that big step in the aircraft control improvement was made, pilots got accustomed to it and finally considered it as normal. However, they soon noted that some limits remained : together with the automatic angle of attacks limitation system, they would also like to have a system limiting load factor at high speed.

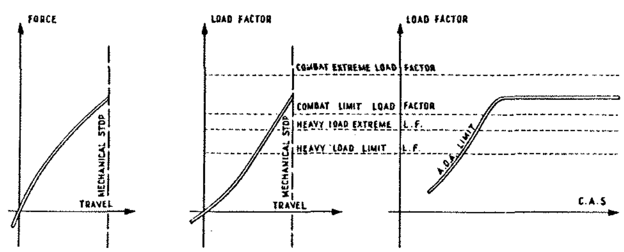
Here comes a requirement whose solution is hard to find : be able to make a steep turn "free minded" - i.e., within the aircraft design load factor - but also be able to pull-up close to the extreme load factor, when necessary, in order to avoid hitting the ground, in case of a desperate manoeuvre.

A first step towards that request consisted to work on automatic gains, in order to allow the pilot to override the load factor limit, but stop his action before reaching the "extreme" aircraft load factor limit. It is easy to see that the plane is protected against break up but the load factor has still to be watched to avoid exceeding the airframe elastic limits (fig. 7).

MIRAGE 2000 fig 7

EVOLUTION OF THE LOAD FACTOR AUTOMATIC LIMITATION

PHASE I

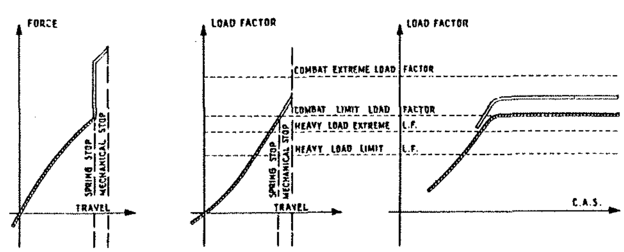


A smart solution to this problem came out of a joint effort from the "Equipment", "Flight Characteristics", "Prototypes" and "Test Flight" departments, in the shape of a "spring stop" (Fig. 8).

MIRAGE 2000 fig 8

EVOLUTION OF THE LOAD FACTOR AUTOMATIC LIMITATION

PHASE II



The spring box giving the pilot an artificial feel of the controls was modified to include a threshold, difficult to go beyond of in normal flying conditions but yet possible with an extra and voluntary effort on the control.

It was then easy to adjust the control effectiveness in order to obtain a limit load factor on the first "spring stop", while keeping a factor inferior to the extreme one on the "mechanical stop".

This was phase 2 of the development.

When the plane was fitted with heavy external loads, it became obvious that the pilot no longer "felt" these loads : the aircraft behaved as in clean configuration.

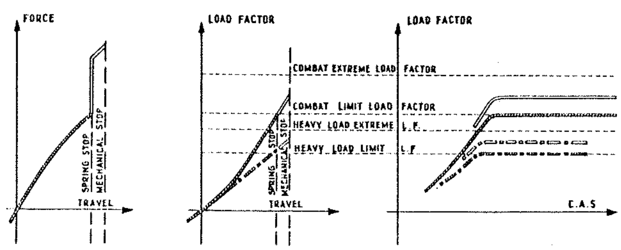
Engineers in charge of structure stress analysis began to feel restless with fear that limit load would be often exceeded, leading to an accelerated airframe fatigue. Nobody ventured giving them any assurance on this, and the pilots least of all.

A new "brain storming" session lead to the solution of phase 3 (fig. 9) : the pilot selects a "COMBAT" or "HEAVY LOADS" configuration on a switch which connects such gains so as to limit the aircraft load factor to a set value.

MIRAGE 2000 — fig 9

EVOLUTION OF THE LOAD FACTOR AUTOMATIC LIMITATION

PHASE III



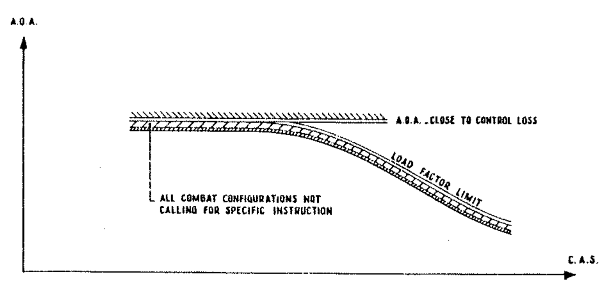
Whatever the configuration, load limit margin remains the same for a given stick force.

We now reach <u>the</u> "fool-proof" machine where the pilot can "hit the corners", anywhere in the flight envelope (Fig. 10).

MIRAGE 2000 — fig 10

AUTOMATIC PROTECTION DEVELOPMENT AGAINST CONTROL LOSS

PHASE II



Well, this is true ... or nearly, as one limit remains which somewhat upsets pilots : below speeds of, say 80 knots, they are not allowed to maintain full back stick.

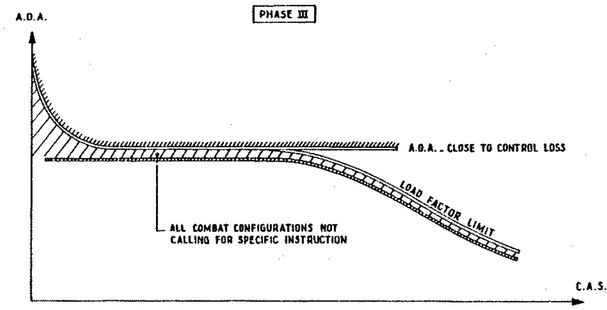
A little combat practice showed that this speed condition occurs quite frequently : pilots then wished to get rid of that constraint.

Aerodynamic data being well known and re-adjusted with flight trials, the "big heads" of the Flight Characteristics department went at it again and found the suitable gains to extend safety handling down to 0 speed. A series of very spectacular trials confirmed calculations (fig. 11) : in order to fool the computer and exceed the recommended angle of attack, the aircraft had to be set in steep climb to decelerate rapidly.

MIRAGE 2000 — fig 11

AUTOMATIC PROTECTION DEVELOPMENT AGAINST CONTROL LOSS

PHASE III



With a 60° initial nose-up attitude, the aircraft would slow-down to 40 Kt, temporarily reaching 35° AoA.

At 80° attitude, speed was 10 Kt and AoA 80°.

In vertical position, the aircraft goes into "reverse" with a 90° plus AoA : we did not find it necessary to graduate the air-speed indicator with negative increments !

Perhaps, I overlooked the point of transverse manoeuvres : the same philosophy was applied, i.e. suppress restrictive instructions as much as possible.

On the MIRAGE 2000, the pilot can go through all longitudinal and transverse manoeuvres he wishes, without considering flight conditions.

However, he still has to make sure that the resulting trajectory shall not interfere with the ground : this safety device is not yet introduced in the black boxes ...

Now, how does the engine behave in these free minded flights ?

In no way does it increase the work load of the pilot who can move the throttle as he likes without worrying over altitude, speed or angle of attack. In no case, a sharp power change from the pilot or caused by a fast variation in flight conditions, should lead to engine trouble.

All military pilots certainly appreciate the huge advantage procured in combat by these characteristics.

Of course, the MIRAGE 2000 conforms to the HOTAS concept (Hands On Throttle And Stick) but on top, it frees the pilot from glancing at the clocks and allows him to keep his eyes stuck onto the hostile and THIS is vital in modern combat conditions.

So, I suggest to extend the acronym to read :

HOTASAFE

Hands On Throttle And Stick ... And Fix the Enemy