PROBLEMS RAISED BY THE APPLICATION OF THE NATURAL STABILITY REDUCTION CONCEPT TO TRANSPORT AIRCRAFT.

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Summary

The concept of natural stability reduction constitutes a potential source of appreciable performance improvement for a transport aircraft. This possibility will be briefly discussed in the first part of this paper.

However, its achievement is subject to various limitations, which will be dealt with one by one :

- problems of integrating the stability augmentation devices in the flight control system
- problems of locating the main landing gear
- problem of control surface effectiveness limitation.

The benefits which can be expected from this concept and the problems to be surmounted in order to take full advantage of it depend on the type of aircraft to which one wishes to apply it.

Thanks to the financial aid of the Direction Générale de l'Aviation Civile and the technical aid of the Service Technique de l'Aéronautique and Centre d'Essais en Vol, we have been able to commence this study on an AIRBUS category aircraft but, above all, on the CONCORDE supersonic transport aircraft on which this concept was successfully tested in flight from March 16th to May 2nd 1978.

1. Integration of the control surfaces in the economic analysis of the aircraft

Orientation of aircraft design to allow favourable integration.

The weight and drag analyses participate considerably in the economic analysis of a civil transport aircraft.

The surfaces required for controlling an aircraft (tail plane, elevons, etc.) appreciably weigh down these weight and drag analyses at the present time (figure 1).

The size of these surfaces and the quality of the aerodynamic forces which they generate (lift and drag) essentially depend on the respective positions of the centre of gravity and aerodynamic centre of the aircraft.

For a subsonic transport aircraft equipped with a tailplane (figure 2) the economic analysis depends on the size of this tailplane and the position of the wing in relation to the fuselage : a tailplane participates more or less satisfactorily in the aerodynamic analysis according to the position of the wing and the care taken in minimizing the aerodynamic interactions.

In the present state of the art, the economic analysis (represented here by fuel consumption) appears as shown on figure 3. In these conditions, the favourable tendency would be to move the wing further forwards and reduce the size of the tailplane.

For a supersonic transport aircraft, which has no horizontal tailplane (figure 4) the control surfaces are essentially the elevons on the trailing edge of the wing.

In this case, it is not so much the size of these surfaces which is important but their participation in the quality of the aerodynamic airflow of the wing area where they are installed : the L/D ratio obtained is essentially connected with elevon deflection.

At supersonic speed, a deflection of about zero provides the best L/D ratio, whereas pitch down deflections are very favourable at subsonic speed (figure 5).

These pitch down deflections are compatible only with an aerodynamic centre forward of the centre of gravity, unless use is made of devices which create a pitch up without affecting stability (slotted moustaches, for instance).

This configuration can be obtained by moving the wing or loading fuel in the rear of the fuselage.

For subsonic and supersonic transport aircraft there therefore exists a common point in the search for an optimum design for performance : moving the centre of gravity rearwards. This movement involves limits which we shall now examine.

Limitation of rearward movement of the centre of gravity.

There are three different types of limitations :

- the first of these limitations is due to handling difficulties : the aircraft becomes unstable when its centre of gravity is moved aft. Stability augmentation systems become necessary. These systems raise problems for designing the flight controls, which will be dealt with in the second part of this paper.
- the second is also due to the stability of the aircraft during roll on the landing gear. The third part of this paper will evoke the problems of landing gear design and location.
- the last limitation is a result of control surface effectiveness which is limited by their maximal operating incidences. The fourth part of this paper will present schemes to improve this effectiveness.

At the end of the first part of the paper, we shall localize these limitations in relation to the others in order to judge the particular points on which efforts should be exerted.

- Subsonic transport aircraft are designed in such a way that the aerodynamic centre is always behind the centre of gravity, at a minimum distance which depends on the general configuration.

This minimum distance is obtained for aircraft loading conditions corresponding to the maximum operational aft C.G. location, and the maximum forward position of the aerodynamic centre encountered in flight. Figure 6 shows the possibilities offered as far as fuel saving is concerned if this distance is reduced.

- In order to keep an adequate load on the nose gear during the various rolling phases at take-off and landing, the ground reaction application points on the main gear must be located to the rear of the aircraft centre of gravity.

It is generally recognized that a load of about 4 % of the total weight is required to ensure adequate adhesion of the nose wheel for steering the aircraft.

For current subsonic aircraft, if the main landing gear is rept in the usual position in the wing, this constraint leads to the limitation illustrated by figure 7.

- At low flight speeds, the control surfaces lose some of their effectiveness : the required effectiveness is achieved by small or large deflections depending on the size of these surfaces. There are limitations on these deflections (tailplane stall, loss of control surface effectiveness at large deflections).

For a subsonic transport aircraft, the maximum negative incidences of the airstream on the tailplane are obtained for centres of gravity **forward** of the aerodynamic centre : the tailplane surface areas required thus decrease as the wing is moved forwards.

The maximum positive incidences are obtained for aft centres of gravity : in this case, the tailplane surface area must be increased when the wing is moved forwards.

Taking these considerations into account, figure 7 shows the tailplane surface areas necessary to comply with the manoeuvrability and trim requirements.

- All these limitations appear in a different form for a supersonic transport aircraft. Figure 8 shows that highly negative C.G. margins must be sought for in order to obtain an appreciable L/D ratio gain. This figure shows the centre of gravity envelope already covered in flight in Spring 1978 with new experimental fly-by-wire controls, and the objective for the second generation supersonic aircraft.

- This objective cannot be achieved at present on CONCORDE owing to the pitch down effectiveness limitation of the elevons. The moment generated no longer increases beyond deflections of about 20°. Considering the large rearward movement of the C.G. beyond the aerodynamic centre, which can be envisaged to optimize performance, the requirements concerning pitch down manoeuvrabilitu rapidly become restrictive.

At its present operational limits, the aircraft has a slight natural instability at low speeds, which is corrected by artificial devices : such a configuration indeed allows the best compromise between handling requirements and performance requirements, considering the fact that we are obliged to consider that loss of the artificial devices mentioned above is not extremely improbable.

- The landing gear location limitations have a lesser effect on supersonic transport aircraft owing to the large size of their delta wing at the fuselage root.

At the end of this first part, it appears that a performance improvement could be achieved for transport aircraft by moving the centre of gravity aft.

For a supersonic aircraft, this movement soon requires a flight control design adopted to the necessity of having extremely reliable control aid systems.

Moving the centre of gravity of a subsonic aircraft rearwards soon raises problems of main landing gear location.

Finally, whether the aircraft is supersonic or subsonic, it is important for the control surfaces to remain effective at large deflections at low flight speeds.

NOTE : We have only considered here the effects of reduced stability on the required control surface sizes or deflections in pitch.

The sizes of the fin and rudder are essentially dependent on power plant design.

A reduction in transverse stability if it were compatible with the requirements mentioned above, would also allow a reduction in fin and rudder size.

II. Problems raised by flight control designs integrating the stability augmentation systems required for handling

First of all, we should note that the problems evoked below are often of the same nature as those raised by the use of conventional aircraft autopilots for all weather landings. The differences will then be due to the bad natural handling qualities of the aircraft involved and the duration of the critical flight phases.

The problems will be due to performance and safety requirements, and the difficulties will increase as the natural stability of the aircraft decreases.

As far as performance is concerned, difficulties often appear at the actuators which transmit the stabilization commands to the control surfaces. These actuators must have a low hysteresis and a high pass band. Indeed, the aircraft-stabilizer-control surface loop can reveal relatively high frequency oscillatory modes if the actuator pass band is inadequate. For instance, the loop reveals a 1 c.p.s. mode on the CONCORDE aircraft, which is a designing case for the actuators (cf. fig. 9).

It could be necessary to eliminate the conventional servo-actuators (driving a linkage which in turn controls power servo-controls) by directly introducing the stabilization orders in electric form into the power servo-controls ; even then, the required pass band could lead to inadequate stability of the servo-controls which would then have to be equipped with corrector networks.

Figure 10 shows a diagram of the hydro-mechanical stabilization network fitted to the CONCORDE power servo-controls. Such a system allows the stabilization, without permanent leakage, of a large pass band servo-control the slide valve of which has no overlap.

It should also be noted that elimination of the servo-actuators appreciably complicates power servo-control design when these servo-controls receive both mechanical and electrical commands.

It is a well known fact that the flexibility of the aircraft can be an important obstacle for designing a large gain "rigid aircraft" stabilizer, on one hand because it excites flexible modes and on the other because of detection of structural modes which we are not always lucky enough to be able to damp like the 2 c.p.s. mode on figure 9.

Independently of performance requirements we also attempt to harmonize the cockpit controls. When we wish to make maximum use of the possibilities of electronics, we design flight controls without a mechanical linkage drive from the cockpit. It is then easy to imagine (and even to produce -cf. Fig. II) miniaturized pitch and roll controls instead of the conventional control columns on civil aircraft, and experience seems to show that these new controls will contribute to improving handling. The yaw controls (and brake controls) then have to be defined in harmony with the previous controls.

As far as safety is concerned, a distinction must be made between the appearance of undesirable control commands and the loss of the system.

It is often easier to protect the aircraft from undesirable high amplitude commands which develop quickly than to protect it from slow drifts or gain variations leading to instabilities. The existence of constant and even, if possible, natural, authority limits (such as maximum servo-control rate) is very reassuring when these limits alone ensure safety. Unfortunately, this is rarely the case and laborious failure analyses can thus prove necessary.

The consequences of total loss of the stabilization system are very directly dependent on the natural aircraft stability. When the aircraft remains controllable in emergency mode without artificial stabilization, the safety problems will be relatively simple to solve. For instance, we could consider it acceptable for one flight in a hundred thousand to be performed without artificial stabilization. The redundancy of the system could be defined on the basis of this objective and on the requirement that take-off be authorized with a single failure, at least for a limited number of flights. It will of course be necessary to look for the common causes of loss of the redundent channels making up the system, and the aggravating causes (failures affecting other aircraft systems, for instance). This process is not always very easy, and for the CONCORDE programm, we have thus had to computer process all the significant failure combinations of the aircraft to make sure than none had been forgotten.

The aircraft now being designed as advanced projects cannot be controlled without artificial stabilization. It is thus more difficult to analyse the system, because this analysis must not omit any common causes, and phenomena which occur less than once in ten million flight hours cannot be neglected. This is why the effects of lightning strikes and static discharge must be studied.

To simplify these analysis problems, we sometimes envisage dissimilar redundancy systems (n identical channels plus p channels different from the first) (cf. Fig. 12). It is not obvious that this dissimilarity alone solves many problems. Indeed, the authority of these systems which are essential for controlling the aircraft will probably be such that an erroneous command could be catastrophique. In addition to this, it is probable that the aircraft will usually be controlled with only one type of active stabilization channel with overall monitoring (such as excessive acceleration detection...). The "common cause" problem will therefore have to be solved for identical channels· In addition, it is more or less certain that these channels will use digital computers which introduce their own specific problem, namely, programming. It seems that it will be very difficult to show that this programming contains no errors, and a solution can be envisaged in double programming and the use of a channel which is more or less dissimilar from the first in the event of disagreement between the results of the two programming operations. It should be noted that monitoring requirements could be the determining factor for fixing the maximum computation durations. It should also be noted that the use of digital computers reduces accuracy problems without removing them completely insofar as sensors remain relatively inaccurate and consolidation point or vote techniques will continue to be used for a long time.

To summarize, we can say that the safety problems have essentially two origins :

- the relatively low reliability of electrical equipment compared with mechanical equipment, whence a high level of redundancy and a farily high complexity of the system and its failure analysis.

- the inadequate present knowledge of the sensitivity of these same items of equipment to static discharge and lightning trike phenomena.

The aircraft performance improvements provided by the reduction of natural stability must obviously not be compensated by an excessive increase in flight control maintenance costs. This means in particular that the system must allow the failed components to be identified easily. All these components, without exception, must be able to be replaced without adjustment on the aircraft. It should also be noted that the problems raised by the present hydraulic fluids used on subsonic civil transport aircraft (erosion of slide valves causing large internal leakage) would be amplified by the use of the servovalves required for electric controls. In fact, maintenance costs should not be an obstacle to the production of flight controls for an aircraft with reduced stability, in particular because of the use of the self-monitored digital computers integrating functions which were dispersed, up to now, in different items of equipment.

III. Main landing gear design and location problems.

As seen in the first part of this paper, the ground roll stability condition (defined by a minimum load on the nose wheel of about 4 % of the aircraft weight) requires keeping a reasonable distance between the aircraft C.G. (G) and the point of application of the ground reaction forces on the main landing gears (R).

If the wing is moved forward in relation to the fuselage (and therefore in relation to the centre of gravity) and assuming that the traditional location of the main landing gear is connected to this wing, there is a problem for providing this minimum load.

At take-off, the load on the nose gear is reduced considerably by the pitch-up due to engine thrust when the engines are housed in underwing pods on a subsonic aircraft.

A take-off procedure involving the gradual application of full engine thrust after brake release allows the minimum distance G R to be reduced. At full thrust, this minimum distance represents 24 % of the aerodynamic mean chord. It is only 15 % for a procedure using only 40 % of this thrust (Fig. 13).

It is in these conditions that the limitations of Figure 14 have been drawn. We can see that this situation constitutes a serious handicap for attempting to improve aircraft performance. We shall now describe a type of scheme which allows point R to be moved back whilst keeping the main gear pick-up bay in the wing.

As it is out of the question to provide a fairing to enable the gears to be retracted into the engine pods or under the wing, the wheels will be housed in the fuselage. The gear bay will be located immediately to the rear of the wing box. It will extend rearwards as little as possible as the cargo compartment is located immediately behind it. As the gear bay is used to house equipment, this equipment could possibly be installed at the front of the bay in order to have the wheels as far back as possible. If we want the ground impact point to be further aft, the rotation which extends the gear must take place around a sloping axis in relation to the aircraft plane of symmetry (cf. Fig. 15). For example, if the gear is 4 metres high, a 10° slope of the axis will move the contact point about 70 cm aft, that is about 10 points of the reference chord for an A.300.B type aircraft. But the vertical forces then have to be transmitted correctly : the hinge axis bearings will usually be naturally located forward of the ground contact point and the loads on the bearings will thus be increased. The gear itself will be offset.

Such a scheme seems to widen the wing movement possibilities and thus increase the associated gains (Fig. 14). But the effects on weight and production costs must not be neglected.

IV. Problems raised by pitch control at high incidence and schemes envisaged

The respective positions of the limitations due to landing gear location and control surface effectiveness show that an appreciable performance improvement can be achieved for a subsonic aircraft by moving the control surface effectiveness limit (Fig. 16), that is, moving the limitations associated with the high operating incidences of these surfaces further away.

The maximum incidences on the tailplane are negative in a conventional design (stable aircraft, adjustable horizontal tailplane) : they are reached during a manoeuvre in landing configuration at maximum forward C.G. around a trim speed appreciably similar to the recommended landing speed (deceleration to stalling speed then recovery, acceleration till the maximum speed authorized for that configuration).

It appears that a variable camber horizontal tailplane with the same surface area controlled directly by the pilot (PHD) would not be subjected to such high incidences during the manoeuvres described above.

Such a scheme would enable the control surface effectiveness limit to be moved back as shown in Figure 16.

When the centre of gravity is moved a long way aft, so that it moves behind the aerodynamic centre, a new limitation connected with the control surface pitch-down effectiveness appears, as stated above.

This limitation is particularly restrictive <u>for a supersonic aircraft,</u> the pitch control surfaces of which are elevons : it cannot be moved back far enough if conventional elevons are used.

The following two schemes increase the effectiveness of the surfaces located at the trailing edge of a supersonic wing, but they could be transposed if required to the pitch controls of a very unstable subsonic aircraft.

- The first scheme consists of adapting a tab on each elevon : this allows us to expect an improvement in effectiveness of about 50 % (see Fig. 17)

- the second consists of providing the elevons with a slot in the leading edge : this does not change the effectiveness at small or moderate deflections, but provides an appreciable improvement at large deflections (Fig. 18)

- Other solutions to the problems raised can also be envisaged ("canard surfaces" for instance).

Conclusion

The attempts to improve transport aircraft performance by reducing stability reveal a certain number of problems essentially connected with the design of :

- flight controls
- main landing gear
- control surfaces.

The evolution in the field of flight controls leading to a progressive use of fly-by-wire controls facilitates resolution of the first type of difficulty encountered : this has already been demonstrated in flight on the CONCORDE supersonic transport aircraft during the spring 1978 campaign.

For a subsonic aircraft, however, we consider it reasonable, in the first stage, to keep a certain number of mechanical controls as an emergency facility.

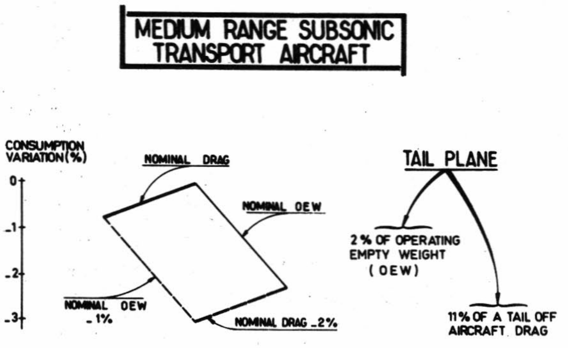
Furthermore, the technological progress made in the field of fly-by-wire controls must be accompanied by parallel efforts in the field of aerodynamic and structural design in order to obtain maximum benefit from the reduced stability concept.

List of figures

Fig. 16 : New position of limitations due to the effectiveness of an adjustable horizontal tailplane and a flying horizontal tailplane for a subsonic aircraft

Fig. 17 : increase in effectiveness of a control surface due to a tab

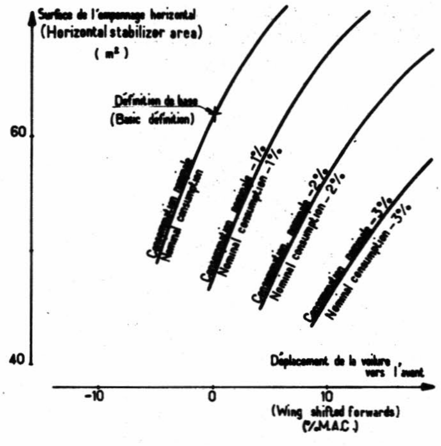
Fig. 18 : increase in effectiveness of a control surface due to a slot.



WEIGHT AND DRAG EFFECTS ON CONSUMPTION

TAIL PLANE PENALITIES

FIG:1



EVOLUTION DE LA CONSOMMATION POUR UN AVION DE TRANSPORT SUBSONIQUE-MOYEN COURRIER.
(CONSUMPTION EVOLUTION FOR A MEDIUM RANGE SUBSONIC TRANSPORT AIRCRAFT)

FIG.3

FIG:2

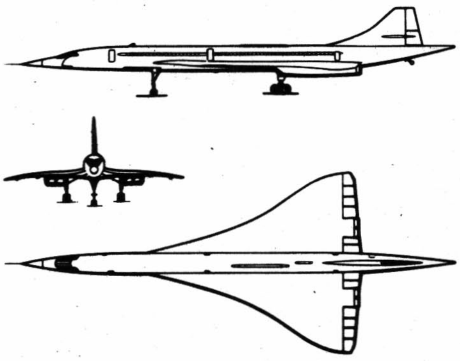


FIG:4
Concorde

_TSS_CONCORDE_

SUBSONIC AERODYNAMIC POLAR FUNCTION OF ANGLE OF ELEVONS

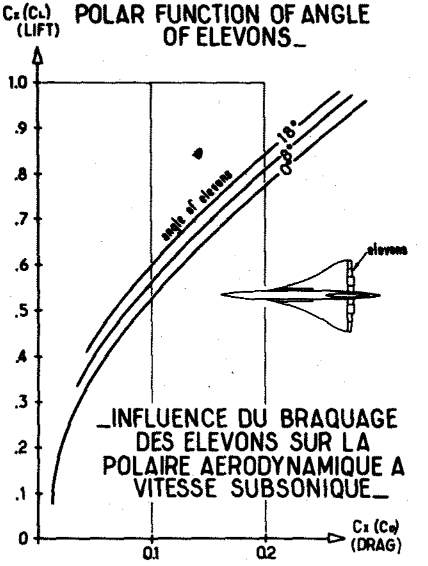
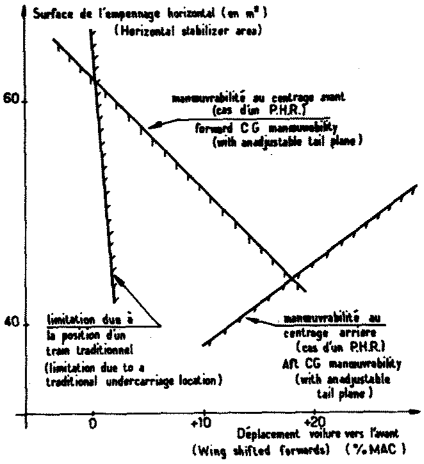
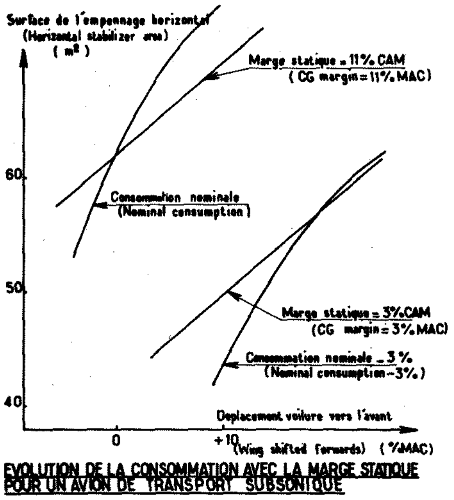


FIG:5



POSITION DES DIFFERENTES LIMITATIONS POUR UN AVION DE TRANSPORT SUBSONIQUE
(SITUATION OF THE VARIOUS LIMITATIONS FOR A SUBSONIC TRANSPORT AIRCRAFT)

FIG:7

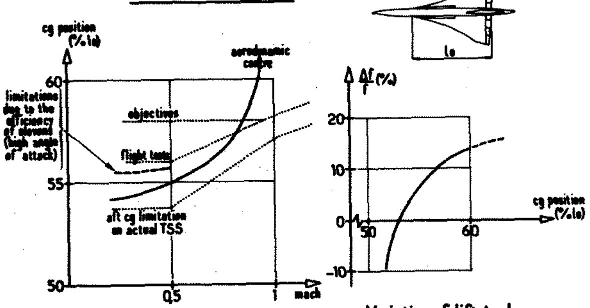


EVOLUTION DE LA CONSOMMATION AVEC LA MARGE STATIQUE POUR UN AVION DE TRANSPORT SUBSONIQUE

EVOLUTION OF THE CONSUMPTION WITH THE CG – MARGIN FOR A SUBSONIC TRANSPORT AIRCRAFT

FIG:6

_TSS_CONCORDE_



aft cg limitation

_Variation of lift to drag ratio = f (cg position)
(lowspeed)

FIG:8

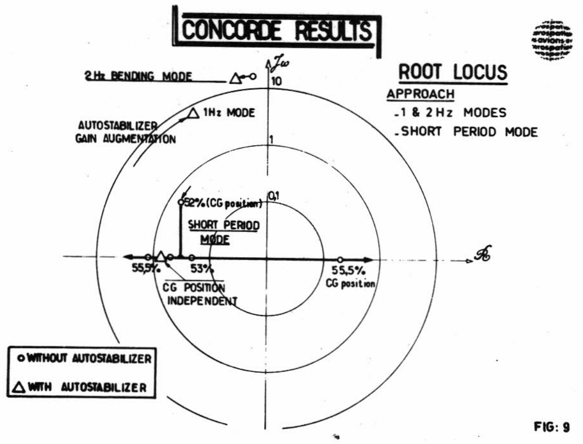


FIG: 9

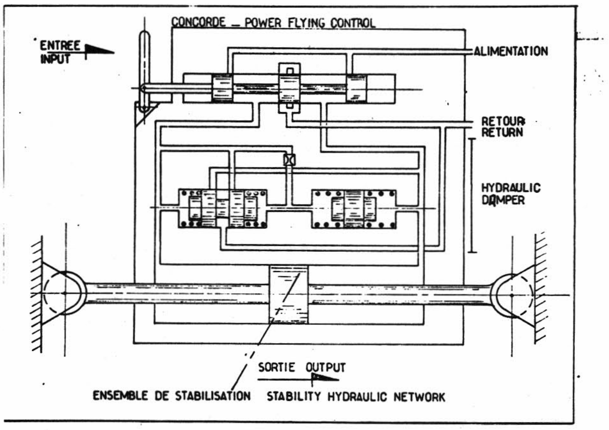


FIG:10

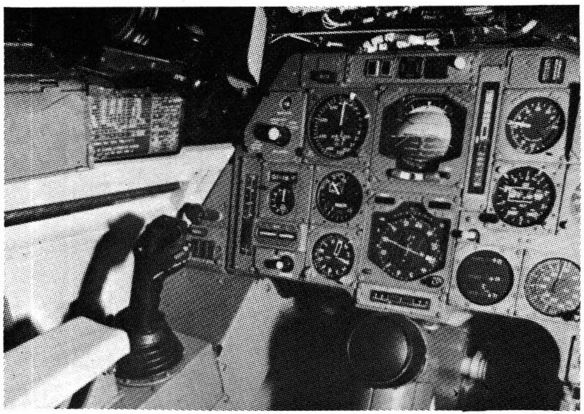


FIG: 11

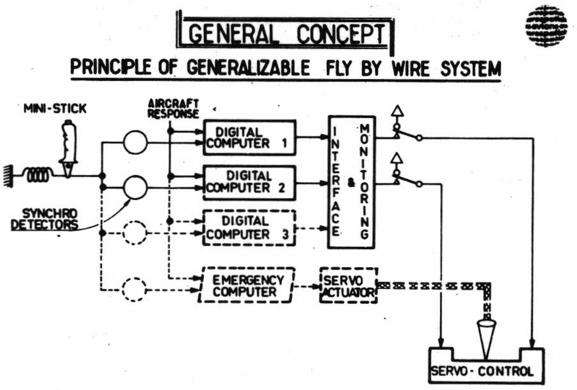
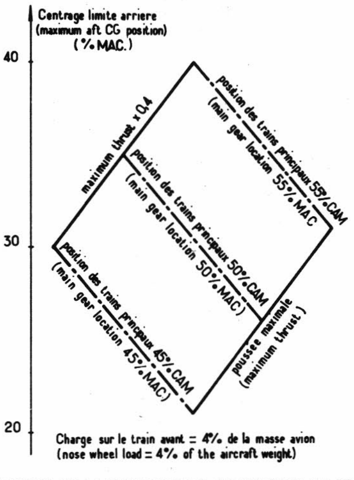


FIG:12



Charge sur le train avant = 4% de la masse avion
(nose wheel load = 4% of the aircraft weight)

EVOLUTION DE LA LIMITE ARRIERE DE CENTRAGE AU DECOLLAGE POUR UN AVION DE TRANSPORT SUBSONIQUE

(EVOLUTION OF THE MAXIMUM AFT CG POSITION AT TAKE OFF FOR A SUBSONIC TRANSPORT AIRCRAFT)

FIG: 13

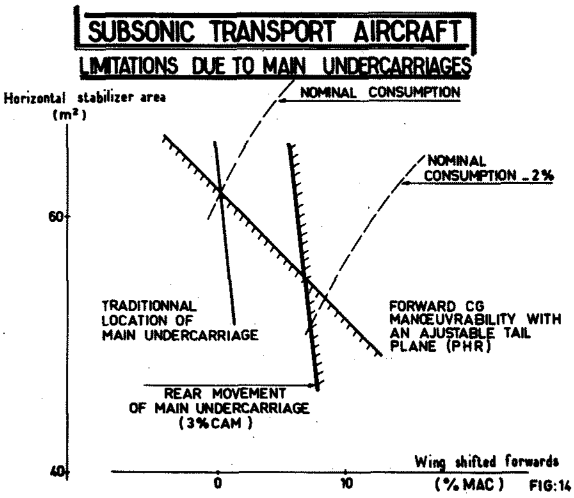


FIG:14

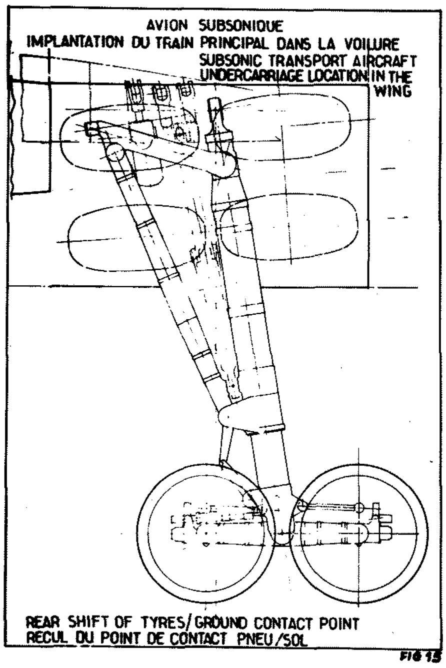


FIG 15

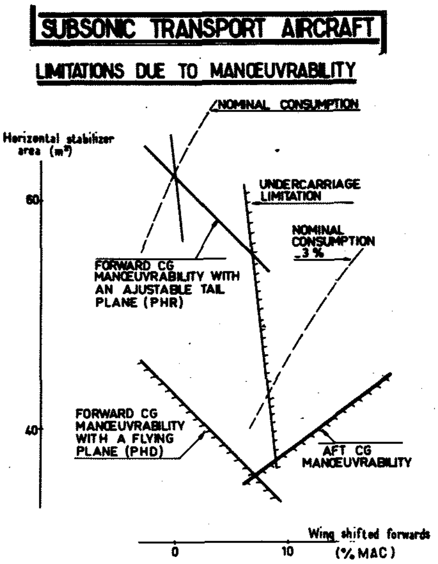
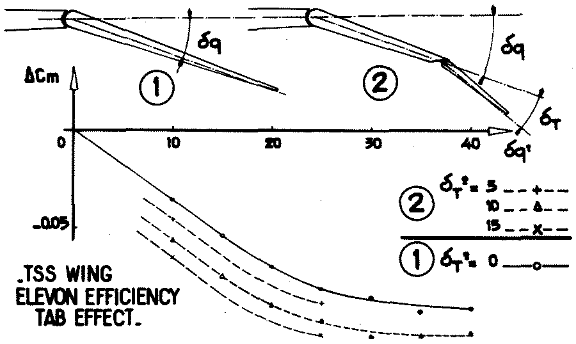
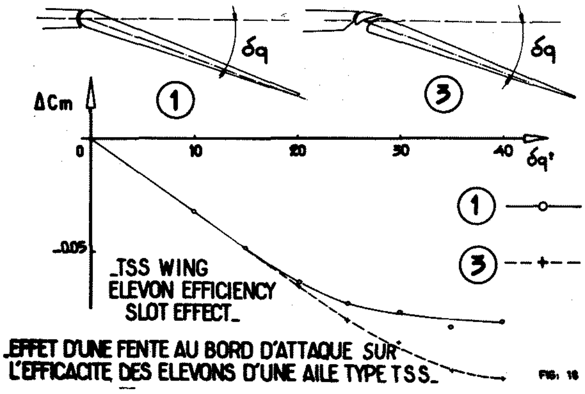


FIG: 16



.EFFETS DE TABS SUR L'EFFICACITE DES ELEVONS D'UNE AILE TYPE TSS.

FIG·17



.EFFET D'UNE FENTE AU BORD D'ATTAQUE SUR L'EFFICACITE DES ELEVONS D'UNE AILE TYPE TSS.

FIG: 18