INVESTIGATIONS ON POSSIBLE CHARACTERISTICS OF FW SUPERHIGH SEATING CAPACITY AIRPLANE

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Abstract

Late in the 1980s TsAGI began investigating superhigh capacity passenger airplanes of a flying-wing configuration. The idea of this concept lies in the possibility of accommodating passengers in the central part of the wing or in the central part of the wing and the fuselage of a lower size than of conventional layouts. In this case it is possible to realize significantly higher L/D ratios, reduce the takeoff weight, improve fuel and economic efficiency. Since the end of 1997 TsAGI has been carrying out the activity under Project 548-97 of the ISTC «Investigations of Technologies Critical for Implementing an Airplane of Flying-Wing Type with Superhigh Seating Capacity».

Computations have shown that the FW configuration, while meeting the requirements similar to those for the B747-400, the largest airplane now in service, can have fuel efficiency by 35% higher and DOC by 22% lower. The investigations are being continued in the direction of aerodynamic experiments and more sophisticated analysis of critical technologies inherent in this layout.

1. Introduction

It was stated in NASA's forecast to 2000 of 1982 [1] for fuel usage reduction of future airplanes that the evolutionary course of advancement due to modifying airplane components tended to be saturated (Fig. 1).

The possibility of further improving the fuel efficiency for unconventional airplane configurations was emphasized.

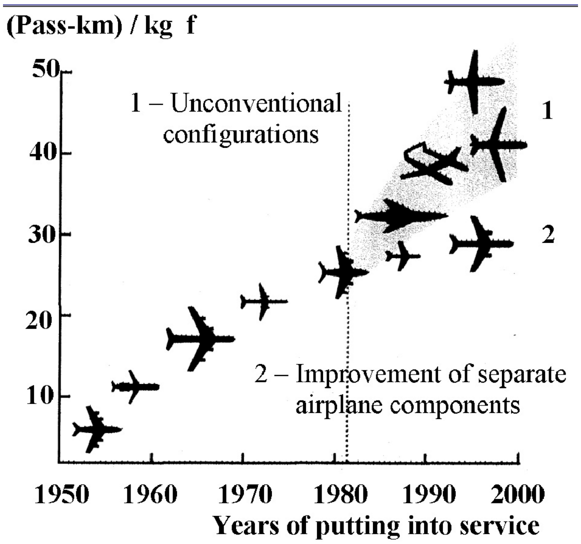

Fig. 1.

Since late 1980s TsAGI has been studying possible characteristics of a flying-wing configuration (FW) with superhigh seating capacity. The first reference to this layout is dated to 1989 [2].

A more detailed analysis of possible characteristics for a flying-wing airplane with engines installed over the trailing edge of the center wing section is presented in the report made at the ICAS 20th Congress in 1996 [3].

At the end of 1997 the International Scientific and Technical Center (ISTC) adopted TsAGI's project No.548-97 "Investigation of Technologies Critical for Implementing an Airplane of a Flying-Wing Type with Superhigh Seating Capacity".

The collaborators of the project are Airbus Industrie/partners (Europe) and Boeing (USA).

One of the main requirements was to limit the degree of static instability ($C_m^{c_L} \le 0.03$) that influenced the engine arrangement.

Preliminary results of the project were reported by the authors [4].

Main results obtained during two-year work under project No.548-97 are analyzed in the present paper.

2. Comparison of various configurations.

The purpose of the work under project No.548-97 at the first stage was to compare the characteristics of various configurations on the bases of multidisciplinary computational analysis and select one of them for carrying out aerodynamic experiments and more detailed calculations of strength, stability and controllability with consideration for the control law developed.

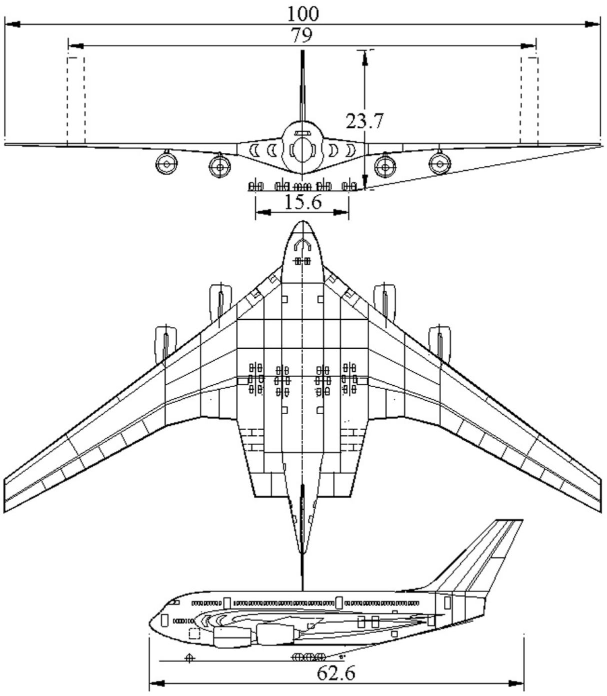

Fig. 2 FW-1 configuration.

As a fragment of the results obtained at this stage of investigations, given is a performance comparison between two configurations: configuration 1 in which a double-deck fuselage is integrated with the center wing section having an enlarged rear extension where 40% of passengers are accommodated (Fig. 2), the engines are located on pylons at the wing leading edge; and configuration 2 with more enlarged center section over the span of the wing with an increased thickness ratio where all passengers are accommodated on one deck (Fig. 3). In this configuration two engines are located on pylons at the wing leading edge, the other two - over the rear surface of the center wing section.

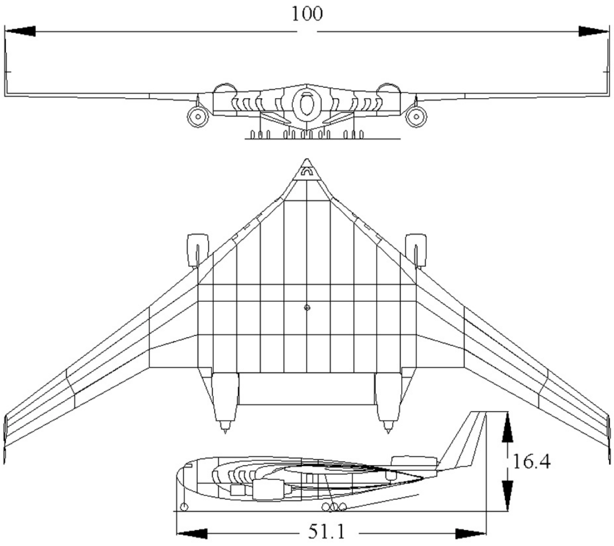

Fig.3 FW-2 configuration

As is seen from the streamline pattern and isobars (Figs. 4,5), there are actually no shocks and boundary-layer separations at cruise (M=0.85, C_L=0.3) in configuration 1, while in configuration 2 there occur boundary-layer shock and shock-induced separation over the outboard wings.

This results in a greater wave-drag rise with increasing a Mach number and more severe reduction of the maximum L/D ratio for configuration 2 (Fig. 6).

For this reason and because configuration 1 is more suitable for meeting the requirements to emergency passenger evacuation, this configuration was selected for further studies.

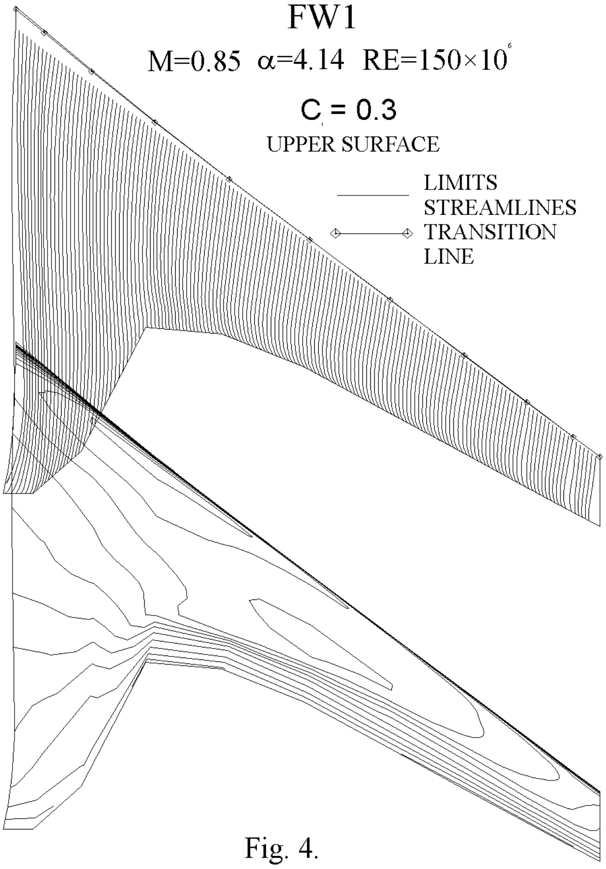

Fig. 4.

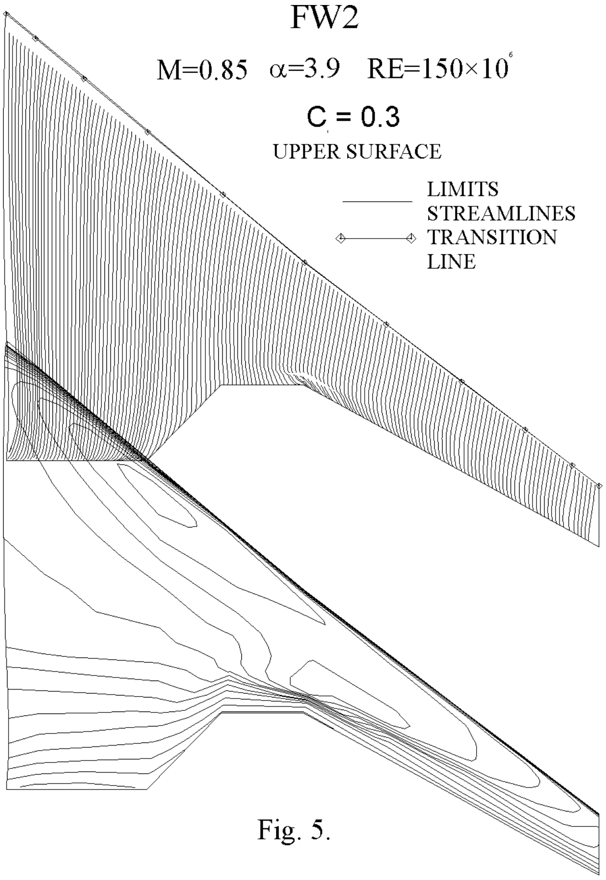

Fig. 5.

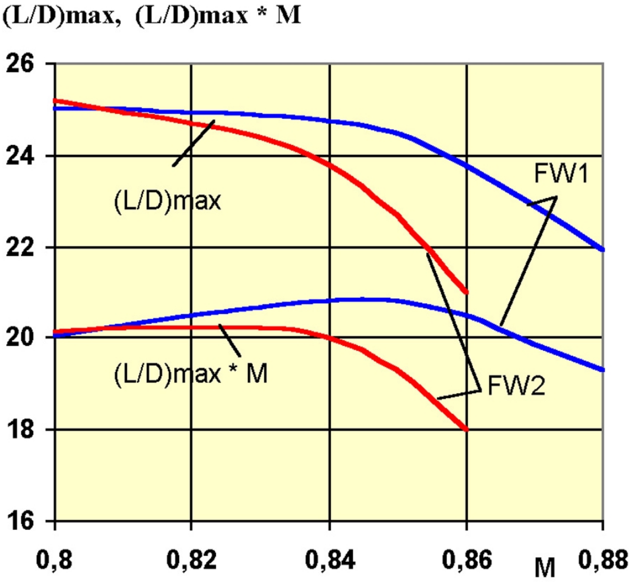

Fig. 6.

3. Experimental investigations

Two aerodynamic models were manufactured:

- to study high-lift devices in takeoff and landing regimes with low flight speeds;
- to study the aerodynamic characteristics in cruise conditions.

A number of investigations in TsAGI’s wind tunnels T-102 and T-106 were carried out.

Fig. 7 illustrates a photograph of the FW-0.85 model designed for investigating the aerodynamic characteristics under cruise conditions in the T-106 test section.

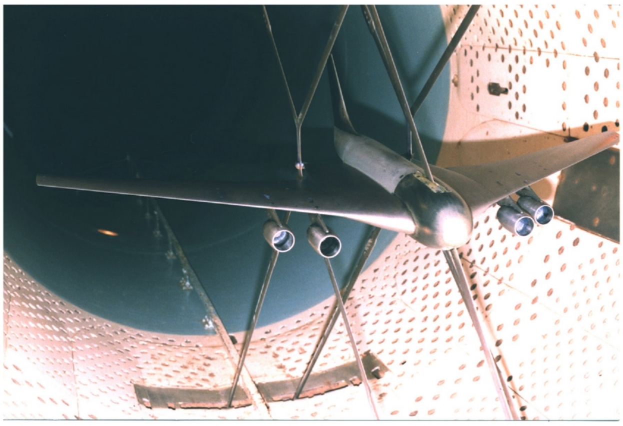

Fig. 7

The results for the recalculation of the values for a maximum L/D ratio obtained in the conditions of the T-106 wind tunnel ($Re=4.75 \cdot 10^6$) as applied to realistic flight conditions ($Re=150 \cdot 10^6$) agreed well with the data of the numerical calculations made previously with using the BLWF program (Fig. 8). We can see that the developed wing shape provides a maximum aerodynamic efficiency $(L/D \cdot M)_{max}$ at a Mach number of 0.85.

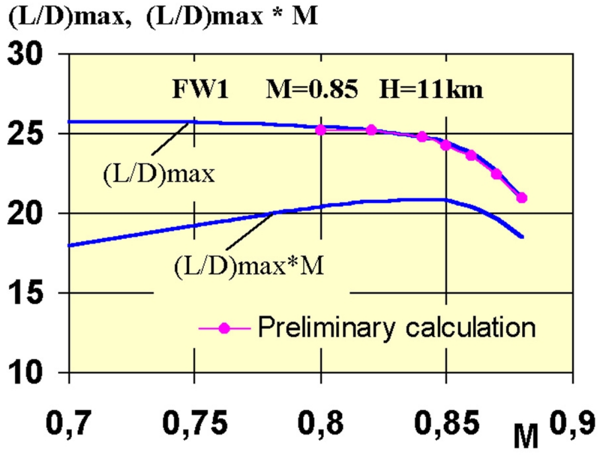

Fig. 8.

4. Structural analysis

In performing these studies, various aspects of strength, aeroelasticity and service life were considered:

definition of the envelope of loads in different spanwise sections of an elastic wing with respect to static cases, action of single gust and continuous turbulence;

effect of elastic wing deformations on the aerodynamic center position and the control surface effectiveness;

study of the wing structure service life and allowable number of flights between inspections for providing a structure survivability criterion.

The investigations were carried out with using a beam model for the outboard wings and a finite-element model (FEM) - for the entire airplane (Fig. 9).

In determining the stresses, required volume of materials and the weight of the load-carrying wing section, of a considerable importance were the peculiarities of a flying-wing configuration that features a considerably larger depth of the wing section in comparison with a conventional airplane (Fig. 10a, 10b). This made it possible to achieve a wing span longer than a conventional airplane has. Besides, the center wing section of a considerable span (~22 m) and with large depth of sections has high stiffness in bending and torsion, which facilitates the solution of the problems associated with outboard-wing flutter.

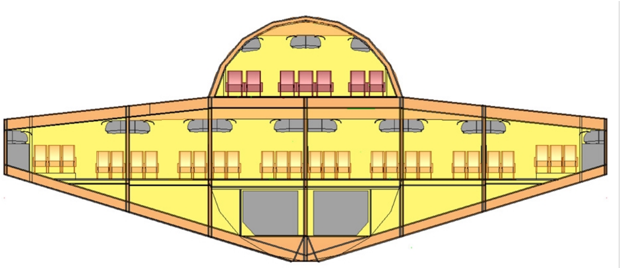

Fig. 10a FW passenger cabin cross section

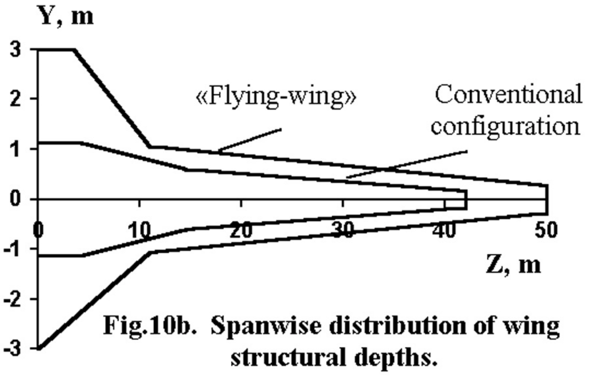

Fig.10b. Spanwise distribution of wing structural depths.

Computation of various flutter modes has revealed that the envelope of all consideredflutter modes provides the flutter onset speed value meeting the standards FAR, JAR (Fig. 11).

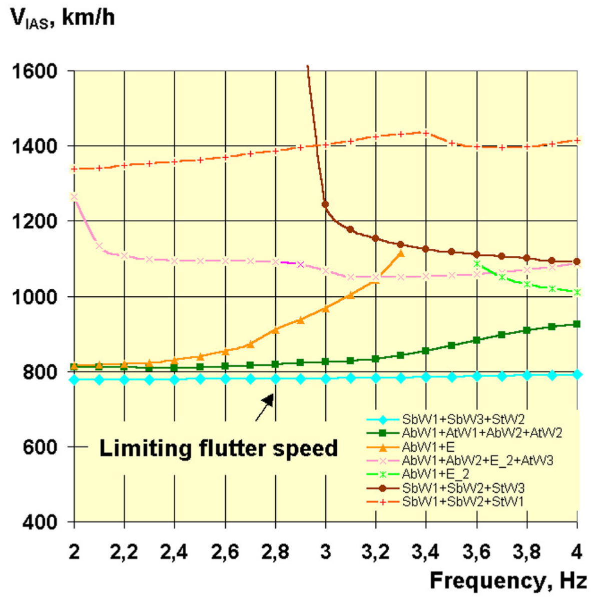

Fig.11. Indicated air speed at flutter: dependence on vertical vibration frequency of outboard engine.

The investigations into service life and survivability have shown that the requirement for 20000 flights for life cycle and 4500 flights between inspections specified by the standards is met.

5. Stability controllability, control systems

Investigations into the problems relating to the reliability of a fly-by-wire control system and flight safety have indicated that the airplane in takeoff and landing regimes is able to have the degree of static stability close to zero ($C_m^{c_L}$ <0), while in cruise flight the instability should be limited by $C_m^{c_L}$ ≤0.03. This required that the configuration considered previously should be revised. Because unlike the conventional configuration, it is impossible to achieve a specified stability margin for the flying wing at aft center-of-gravity limit through selecting a wing position relative to the fuselage, the main way is to select the location of engines on the airplane.

The configuration with engines arranged over the wing tailing edge considered early at TsAGI [3] as well as the layout described by R. Liebeck in Ref. [5] have a high static instability not meeting the requirement $C_m^{c_L}$ ≤0.03.

Therefore, out of the layouts considered selected was configuration 1 shown above (Fig. 2) with engines arranged on pylons at the wing leading edge, typical of conventional configuration airplanes.

The problem of making it possible for the flying-wing airplane to recover from flight at high angles of attack (for example, in demonstrating a stall speed) to moderate angles of attack is difficult. According to experimental investigations, at aft c.g. limits ($\bar{x}_{c.g.}$=0.34) the airplane has a significantly nonlinear behavior of the longitudinal moment coefficient at high angles of attack (Fig. 12). In this case a maximum coefficient $m_Z(\alpha)_{\max}$ is achieved at angles of attack of about 20°, then it decreases to m_Z=0 at the angle of attack equal to ~24°. This point is a unstable equilibrium point ($C_m^{c_L}$ >0) and to recover to moderate angles of attack the possibility of reaching negative values m_Z for the range of angles of attack from 5°<α<24° is required. With the angle of attack 5° the flying-wing airplane could be trimmed without elevon deflection (Fig. 12).

Experimental investigations have revealed that the wing root elevon deflection together with slat extension and the displacement of controls on the aft part of the center wing

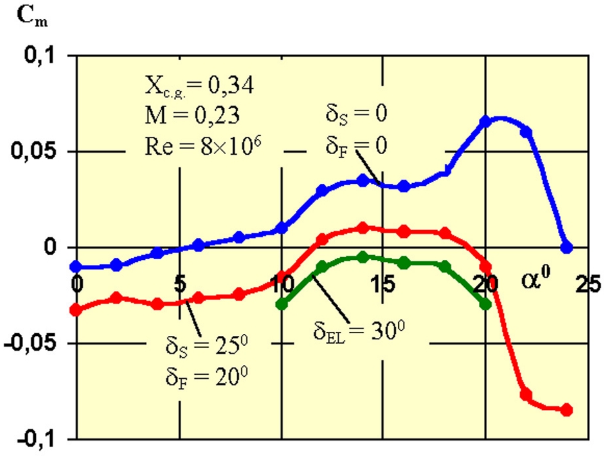

Fig. 12.

section can provide the FW recovery from α=24° to α=5° (Fig. 12).

To fly in a cruise configuration within the entire range of flight conditions, including cruise M=0.85, the algorithms for limiting ultimate modes are realized by the control system:

- angle of attack at low speeds and altitudes (Fig. 13);

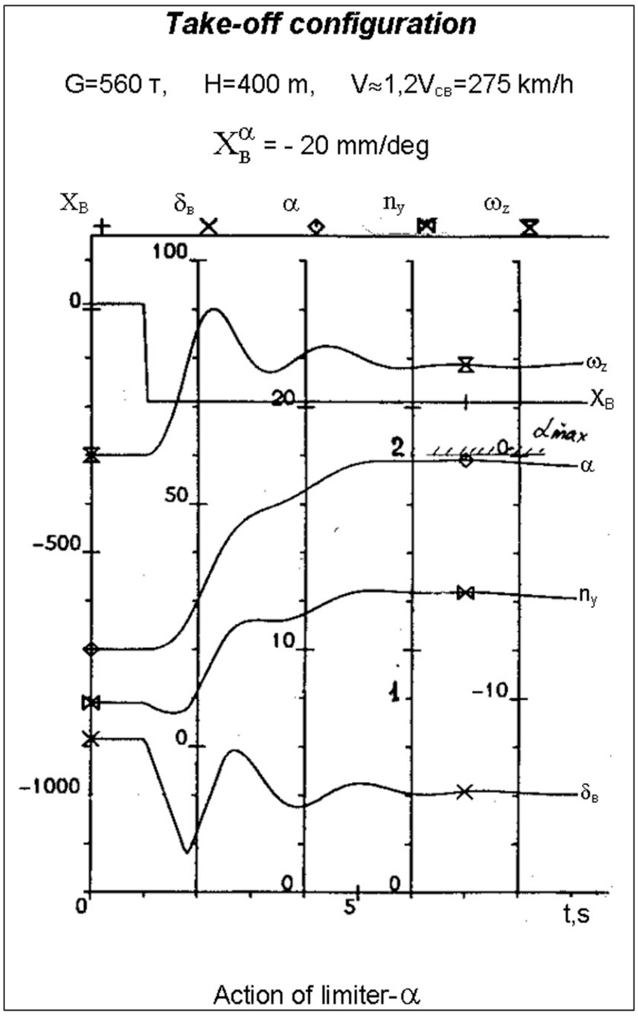

Fig. 13.

- normal g-load n_Y (Fig. 14);
- maximum roll angle in lateral movement.

The restriction of ultimate modes prevents the achievement of high angles of attack in a possible flight envelope.

The possibility of providing cruise flight in self-trimming mode (m_Z=0) without elevon deflection is a significant factor for the airplane in a FW configuration, because the elevon deflection results in higher losses in aerodynamic efficiency as compared to the trim provided by controls on the horizontal tail of the conventional aircraft.

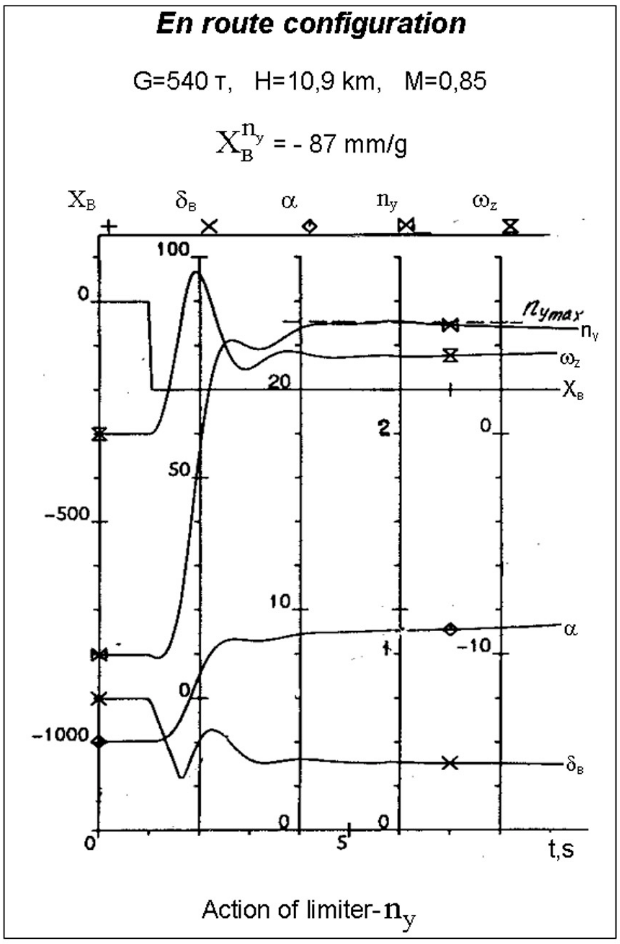

Fig. 14.

There are free volumes in the wing box of the FW airplane (the capacity of 199t of fuel is required for flight for design range and en-route fuel reserve while the wing volume allows one to accommodate 280t of fuel). In case of fuelling the tanks beginning from the wing tip the aft c.g. limit can be provided (upper curve in Fig. 15). If the tanks nearest to the aircraft plane of symmetry are fuelled first the forward c.g. limit will be realized (lower curve in Fig. 15).

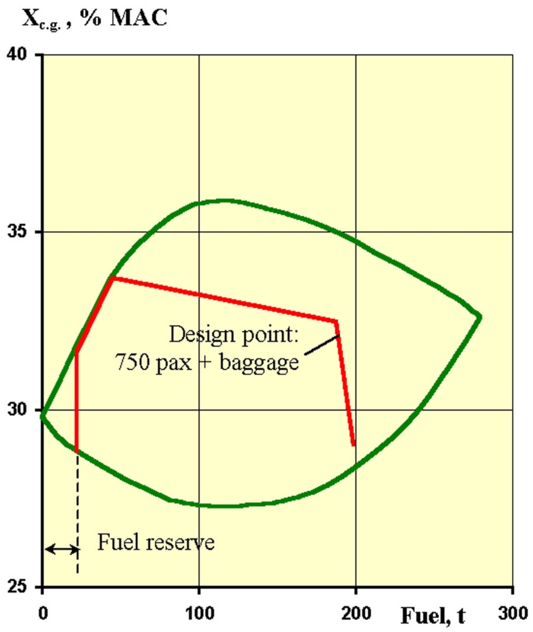

Fig.15. $X_{c.g.}$ position versus fuel location.

In the interspace between these curves by choosing the initial fuelling and an appropriate fuel utilization (and transfer) during the flight one can derive c.g. positions required for takeoff, landing and cruise flight in the self-trimming mode. The exception is the last portion of flight for design range of 14000 km (distance ~1300 km, fuel consumption ~20t) where trim by controls has to be used, because the remaining fuel is insufficient for achieving the c.g. position required for self-trimming (Fig. 15).

Variations of the FW center-of gravity position in flight for design range and the position of aerodynamic center ($\bar{x}_{a.c.}$) of an elastic aircraft versus flight weight are given in Fig. 16.

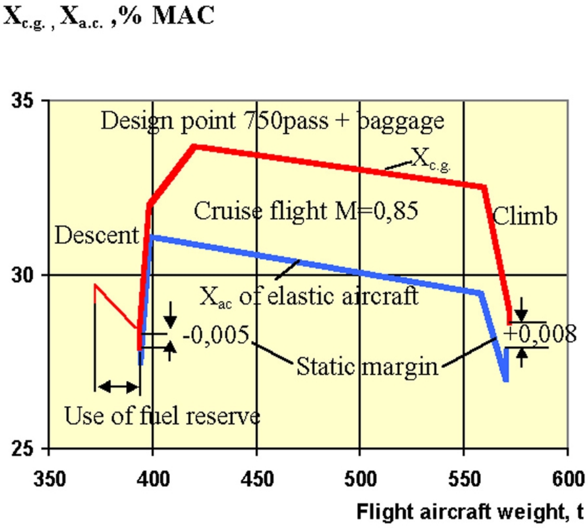

Fig.16. Variation of aerodynamic-center and c.g. positions.

Static stability $C_m^{c_L}$ ~0 is provided in takeoff and landing modes, while in cruise flight static instability $C_m^{c_L}$ ~0.03 is realized.

6. Comparison of characteristics of airplanes in Flying Wing and conventional configurations

A multidisciplinary analysis carried out under Project No.548-97 is aimed at revealing possible advantages of a FW airplane over a conventional configuration with equal passenger capacity, range and technology level. For these purposes a conventional airplane was configured, its parameters were optimized and characteristics relating to all disciplines estimated.

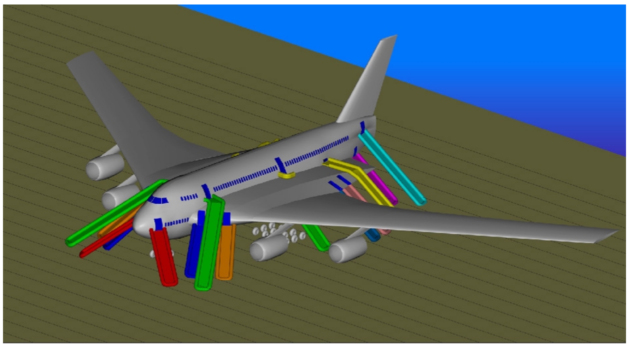

Fig.17.

The study on the problem of emergency evacuation of passengers is an important issue when comparing the FW and conventional configurations. The system of escape slides for the FW airplane (Fig. 17) mainly corresponds to that of a double-deck airplane with high passenger capacity. The distance to the nearest exit in the lower deck of the FW airplane with the exits blocked along one side is longer as compared with the conventional configuration (Fig. 18).

To eliminate this disadvantage, the width of longitudinal and transverse aisles in the lower deck of the FW airplane is increased.

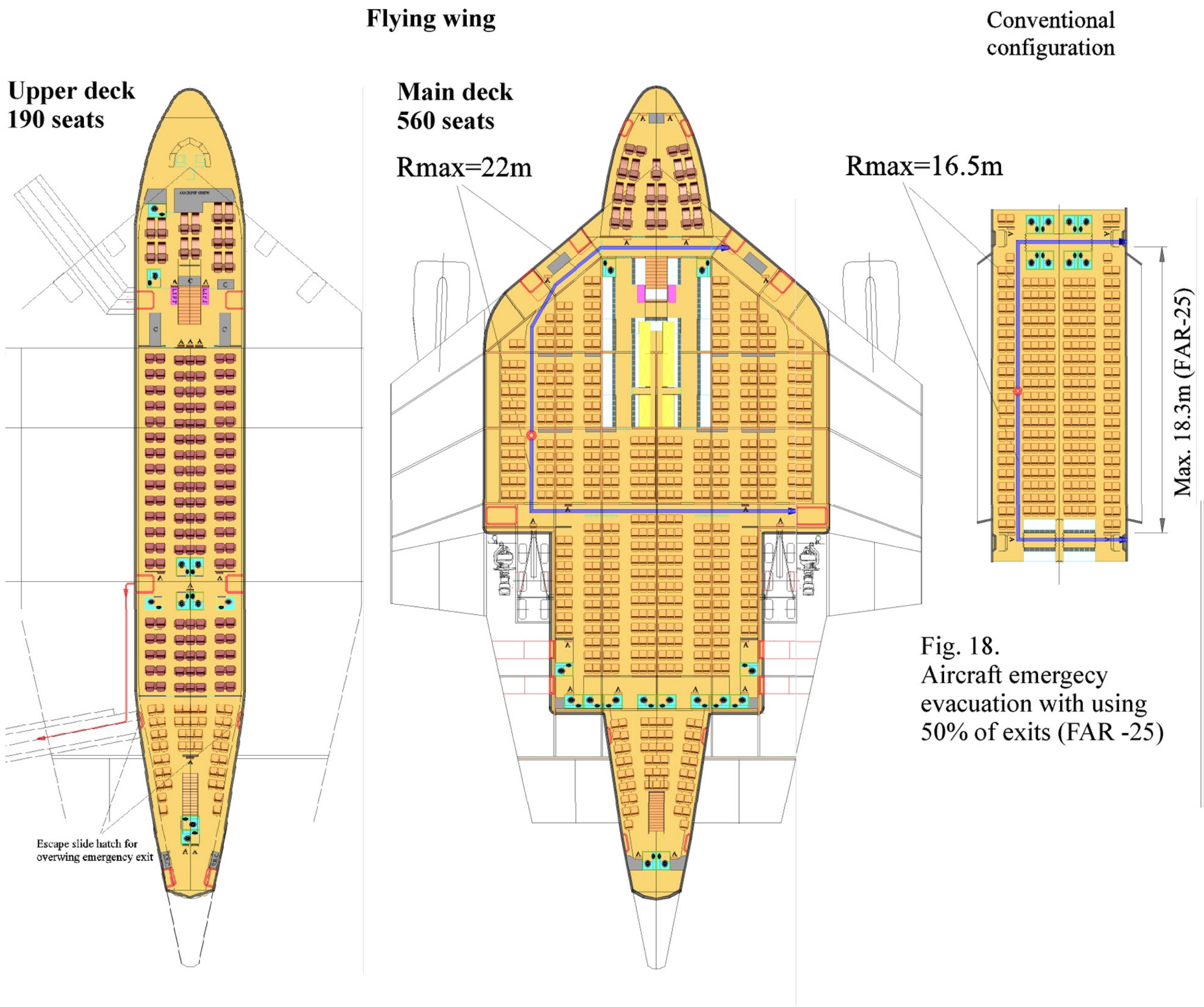

Fig. 18.
Aircraft emergecy evacuation with using 50% of exits (FAR -25)

7. Conclusion

Theoretical and experimental investigations carried out under ISTC Project No.548-97 made it possible to compute the characteristics of the FW airplane which are superior to those of the conventional configuration with equal requirements and technology level (Table 1).

Table 1.

The FW configuration has:	
Takeoff weight	13.4% lower
Operating empty weight	6.3% lower
Single engine thrust	12.7% lower
L/D ratio	22.0% higher
Fuel consumption per flight (L=14000 km)	25.5% lower
Airplane cost	4.8% lower
DOC	8.1% lower

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