Computational and experimental studies on the high speed subsonic airliner with M_{cruise}=0.9

Bolsunovsky A.L., Buzoverya N.P., Chernavskyh Yu.N., Chernyshev I.L., Skomorohov S.I.,
TsAGI, Russia.

Computational and experimental studies on high-speed subsonic airliner with M_{cruise}=0.9-0.92 have been carried out at TsAGI in the last years to provide in-depth information about the possibility of creating faster than usual long-haul airplane. The design methodology is discussed together with wind tunnel results. In the author's opinion reducing the speed level slightly compared with near-sonic airplane allows the designer to obtain really "healthy" project with less technical risk and not so much increased weight and fuel consumption, but still providing noticeable trip time saving.

Introduction

According to the famous Kuchemann's thesis the time of a pleasant trip for a passenger should not exceed two hours. While such desire is just only a dream, the attempts to increase aircraft speed are strongly welcomed by public community. Besides passenger comfort higher speed yields increased productivity of the airplane. Some times a discrete qualitative improvement occur when it is possible to service particular line by using fewer faster airplanes, say two instead of three, with corresponding reduction of acquisition cost, flight crew salary etc. Unfortunately a strong trade-off between efficiency and speed exists for current technology level jet transport. Not only large supersonic transport with its so far unsolved sonic boom problem, but even near-sonic cruise airliner would suffer from increased fuel consumption. The history of aviation knows several attempts to develop near-Mach 1 passenger airplane, but each time high oil prices killed this initiative: in the early 70-s [1,2] and at the threshold of the centuries, when the ambitious "Sonic cruiser" program was abandoned in favor of the B-787 "Dreamliner" development [3]. The irony of the technical progress in aviation is that even now, 40 years after its first flight, the B-747 [4] is, and most likely will continue for a long time to be the fastest large passenger aircraft in the world.

There are two possible ways to attack near-sonic range of velocities: to take pure supersonic configuration with broad delta planform and slow it down [3,5] or to take a conventional subsonic configuration and speed it up [1,2,6]. Both possibilities have been studied thoroughly at TsAGI recently in the course of advanced long-haul aircraft studies. Two important questions have been tried to answer: is it possible with the last advances in aerodynamics (like those described in [6]), propulsion, structures and systems to create economically competitive near-sonic aircraft; and what type of configuration is more appropriate and for what speed range. This article concerns the selected results of experience obtained with the second approach of speeding up the conventional configuration with swept wing. In the author's opinion reducing the speed level slightly – from M_{cruise}≈0.95-0.98 to M_{cruise}≈0.9 allows the designer to obtain really "healthy" project with less technical risk and not so much increased weight and fuel consumption, but still providing noticeable trip time saving.

1 Design considerations and methodology

One of the challenging tasks for Russian aviation industry in the nearest future is connected with the creation of advanced moderate capacity moderate range airplane – successor of the very successful in the past IL-62. Such an airplane is necessary for servicing thin long air-routes typical for Russia (Fig.1); at the same time it has some export potential of providing point-to-point service for city pairs with moderate population, while very large airplanes are more suitable for hub-and-spoke route system. Notice that moderate design range of about 5000nm yields significant reduction of the MTOW compared with aircraft capable with very long range [7] and therefore results in less environmental pressure – factor which may become crucial in the future.

In the course of the studies upon advanced long-haul aircraft the influence of cruise speed on the wing shape has been investigated. To this end three research configurations with progressively increased M_{cruise}=0.85, 0.88 and 0.9 were computationally designed, manufactured and tested in the large transonic wind tunnel T-106 (Fig.2). For the last layout M_{MO} was prescribed not to exceed 0.92 in order to restrict dive speed by subsonic limit. Wings were mounted in a low position on the body with fairly small fairings. All the layouts use the same simple cylindrical non-“area-ruled” fuselage. At present it is commonly agreed that although very beneficial for favorable interference with the wing [2], “area-ruling” of the fuselage brings additional complexity and weight together with complicating passenger accommodation.

Of course, the sweep back angle of the wing increases and thickness-to-chord ratio decreases with the increase of cruise Mach number. It was decided to remove leading edge extensions at the root, typical for near-sonic airplane [2] and to add structurally more useful trailing edge extension. For M_{cruise}=0.9 design both sweep angle ($\chi_{1/4}$=38.5º) and thickness-to-chord ratio have been chosen close to that of the B-747 wing (Fig.3,4) with the thought in mind to preserve satisfactory take-off&landing performance by using conventional (slat/flap) high lift devices. Root-to-tip washout of the wing equals 6 degrees.

Despite the increased sweep the design of the aerodynamic configuration with very high Mach number is significantly complicated even compared with M=0.85 design. Strong shocks may exist not only on the wing but on the top surface of a fuselage or in the region of cockpit-cylindrical part juncture. The role of the aerodynamic design tools changes, for example, besides the creation of a wing surface it is useful to apply inverse methods also for formation of the fuselage geometry and generation of "aerofunctions". During optimization it is worthwhile to vary wing planform because of difficulty to reach rational shape basing on the previous empirical relations. Off design conditions at Mach number below and above the design value may be easily disrupted if not taken into account properly. Matching high subsonic Mach number cruise performance of a wing with high-lift capability during take-off and landing is complicated due to increased sweep and decreased thickness of the wing sections.

All above issues have been incorporated into the aerodynamic design process. A key element of the aerodynamic design methodology is the optimization procedure [8] in which several flight regimes are treated simultaneously including maximum lift coefficient regime at low speed. The geometry of the wing is defined by six baseline sections along span. Geometry variations utilized in the study are base section profiles variations together with some wing planform defining parameters. They can be local smooth variations, global variations of a contour, such as change of thickness or camber, position of the maximal ordinate along chord, vertical displacement, twist variations, nose or tail deflections, etc.; finally, they may be differences of coordinates of known airfoils. On an average about ten geometry variations are attributed to each wing base section. Five cruise regimes have been taken into account: M=0.9 Cl=0.46; M=0.91 Cl=0.45; M=0.92 Cl=0.42; M=0.91 Cl=0.41 and M=0.9 Cl=0.525, all at wind tunnel conditions $Re=3.5\cdot10^6$ Xtrans=0.1. The last regime was included for controlling buffeting behavior. The number and exact definition of cruise regimes as well as relative importance of each were determined by lengthy try-end-error procedure after the analysis of optimization runs results. Thus it is crucial to use fast transonic (BLWF) and subsonic (WSEP) analysis methods [9] to fulfill numerous flow evaluations in optimization loops without excessive time consumption. During optimization not only aerodynamic features but also the requirements on the wing surface curvature are taken into account in order to obtain smooth shape along chord and span with acceptable manufacturability.

Computed pressure distribution over the wing at first design regime M=0.9 Cl=0.46 is shown in Fig.5. Only fair shocks are seen on the outer wing giving moderate integral wave drag value of $Cd_W \approx 0.0005$. The load distribution is close to the elliptical one. According to CFD calculations there is no separation on the wing surface (Fig.6). Computed M_{DD} values (0.926 at Cl=0.35; 0.922 at Cl=0.4; 0.915 at Cl=0.45 and 0.91 at Cl=0.5) have been decided to be satisfactory. Besides, estimated values of Cl_{buffet} at cruise and Cl_{max} at M=0.2 showed sufficient margins for safe flight.

Special attention was devoted to the design of the fuselage nose section. More bluff nose is preferable for high Mach number cruise in order to prevent the appearance of the shock over the joint with a cylindrical part of the body. Nonsymmetrical blunt nose section was specially designed to produce some additional lift, which helps to reduce wave and trim drag.

2 Experimental studies

Basing on the fulfilled computational design, the aerodynamic model of the M=0.9 airplane has been manufactured and tested in the large TsAGI's transonic wind tunnel T-106. It is a fan-driven, closed-circuit wind tunnel with perforated circular cross-section (D=2.48m) (See fig.2). The wing of the model was made of chromansil steel. Positive extra washout of $\Delta\varphi=1^o$ was incorporated into the model in comparison with theoretical flight twist to account for aeroelastic effects at large wind tunnel dynamic pressures. The span of the model (L=1.64m) was thought to be properly balanced with the wind tunnel dimensions even for the largest transonic Mach numbers up to M=0.95 in the experiment.

Wing tunnel campaign was carried out in May 2008. Free and fixed transition runs were fulfilled at different Mach numbers: from the smallest value M=0.2 to the highest one of 0.95. Typical cruise Reynolds number based on mean aerodynamic chord of the model (MAC=0.24m) equals approximately 3.5 mln, so significant laminar flow regions exist on the wing. Fixing of the boundary layer transition at both wing surfaces was done by trip disks with the height of ~ 0.15mm placed along the span at 10% chord position. Both wind tunnel techniques have their own cons and pros; the reader can found details in special references. For example, the drag increment resulting from the trip disks is not trivially determined value, especially at high transonic speeds, when shock position and strength are sensitive to the boundary layer thickness [10].

As an example of experimental data lift and pitching moment curves for free transition conditions at Mach numbers M=0.2, 0.85, 0.9 are shown in Fig.7. It is seen that the behavior of both characteristics is acceptable; there is sufficient margin for fulfilling 1.3g maneuvers; small non-linearity at cruise is the result of transition point movement. The L/D and M*L/D-curves vs M are plotted in Fig.8 for both free and fixed transition conditions. Maximum of aerodynamic range parameter M*L/D exists exactly at M=0.9 for fixed transition condition and even at greater M=0.91 at free transition condition. It means that the primary goal of the design have been reached successfully.

Conclusions

An aerodynamic model of the high-speed subsonic airliner with $M_{cruise}=0.9$ has been designed and successfully tested in a large transonic wind tunnel. With the new wing parameters (sweep angle and thickness-to-chord ratio) being similar to that of the B-747 aircraft the designed configuration thanks to utilization modern supercritical profiles is really capable to ensure economical flight with much higher speed ($\Delta M \sim 0.05$). Orientation to the lower limit of near-sonic speed range permits to obtain really "healthy" project with less technical risk and not so much increased weight and fuel consumption as for "pure" Mach One configuration, but still providing noticeable trip time saving.

References

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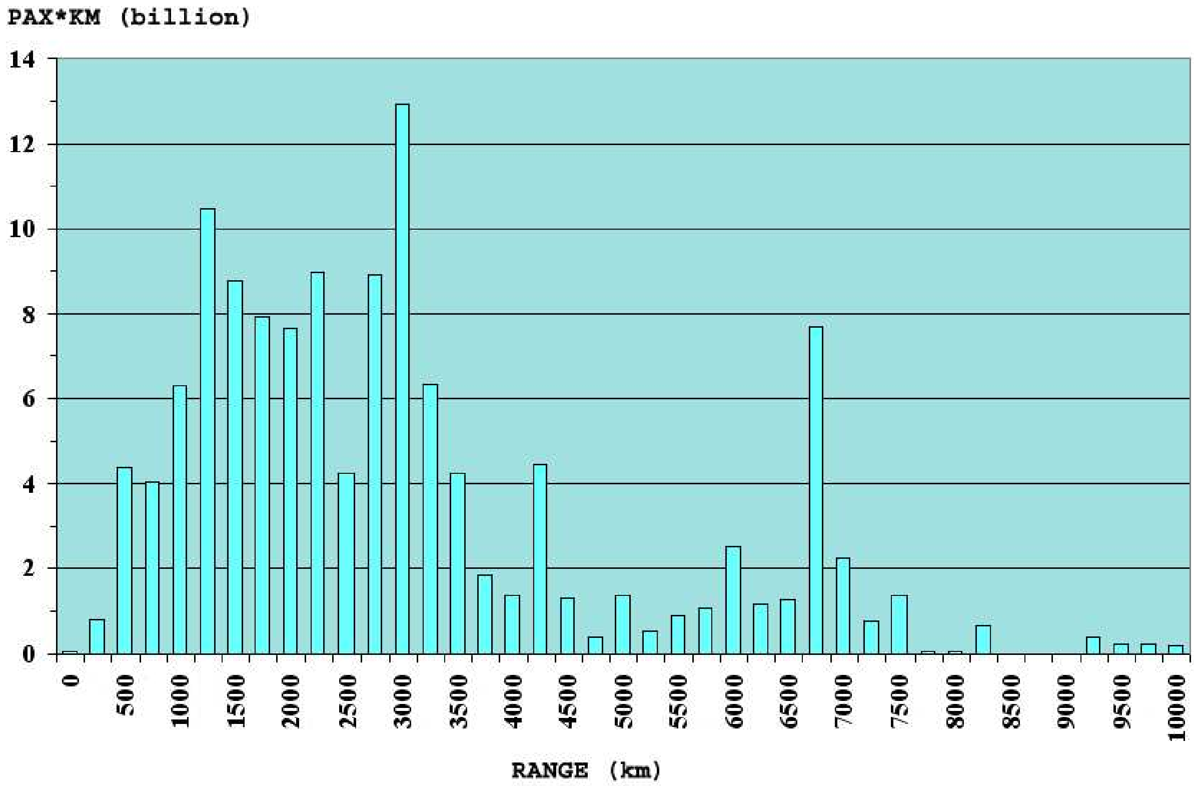

Fig.1 – Distribution of pax-range density for Russian airlines (2007)

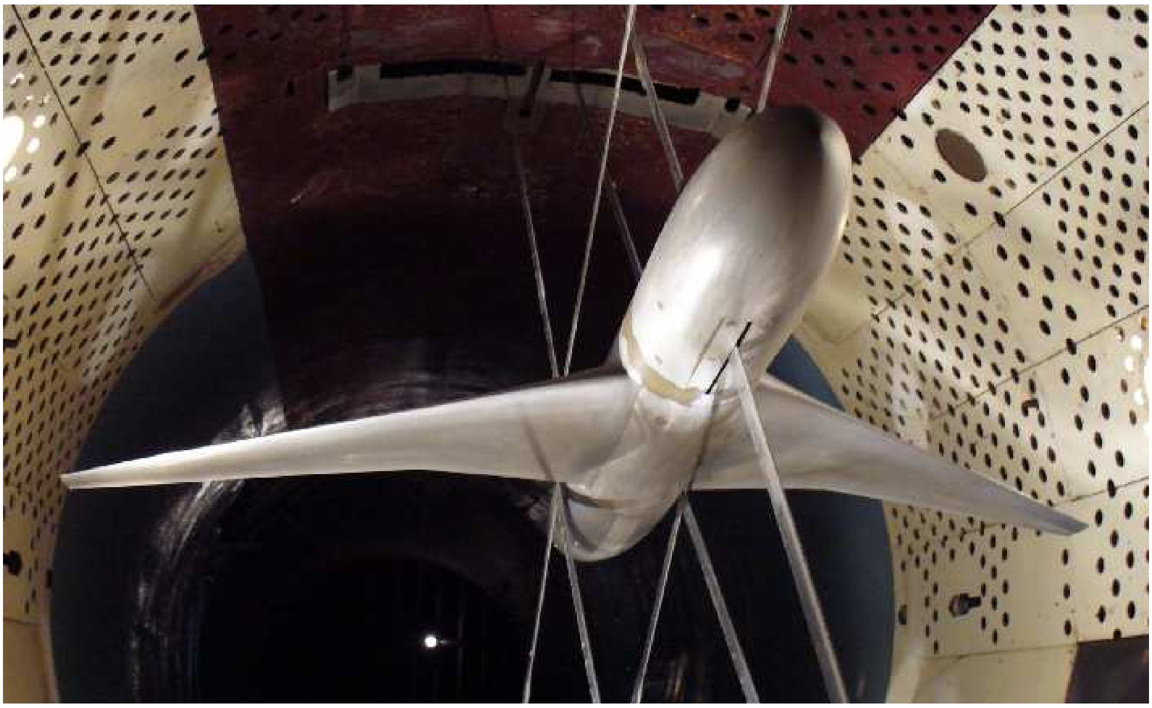

Fig.2 – Aerodynamic model in T-106 wind tunnel

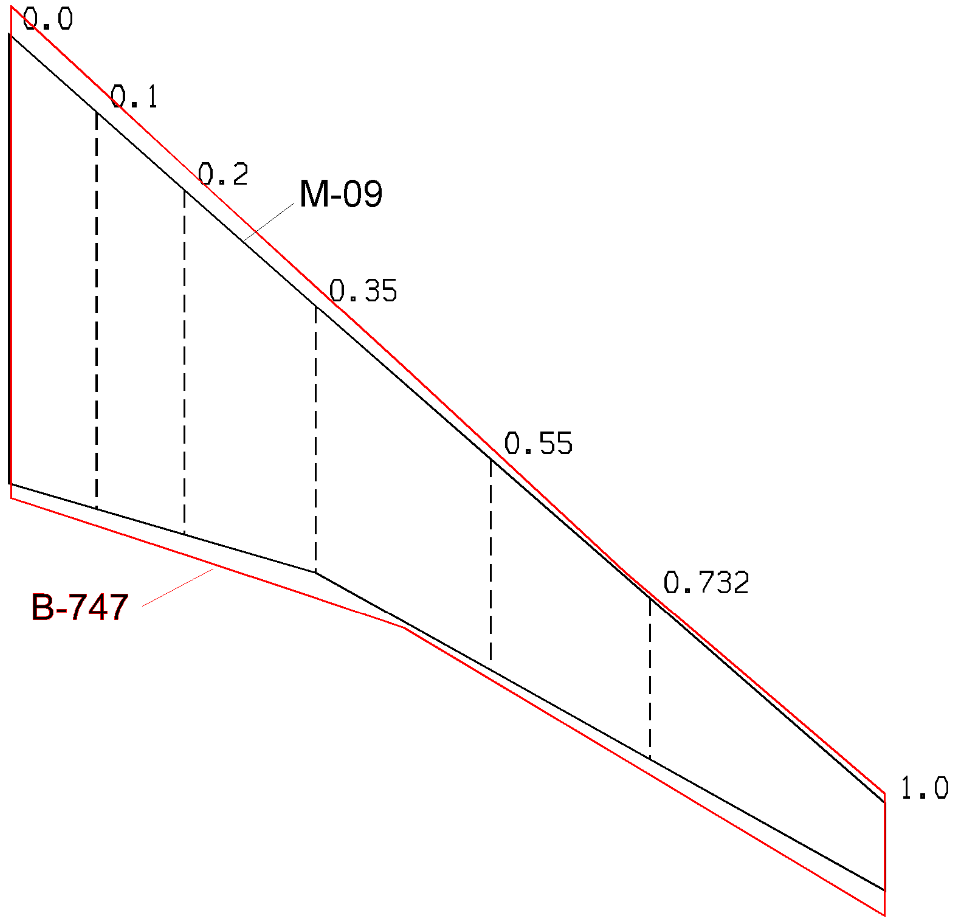

Fig.3 – Planform comparison

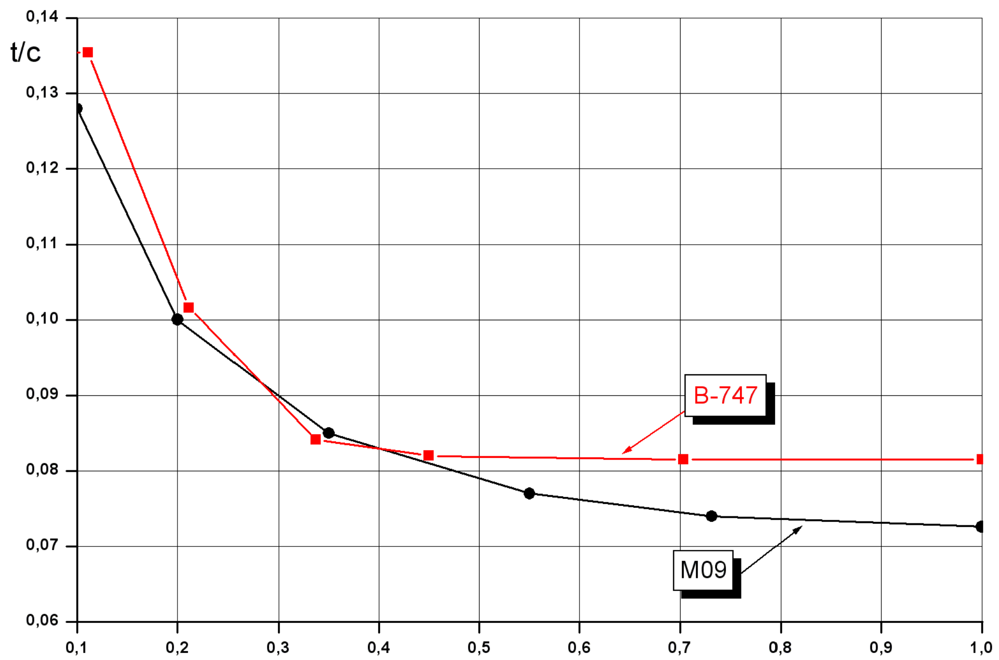

Fig.4 – Comparison of thickness-to-chord ratios

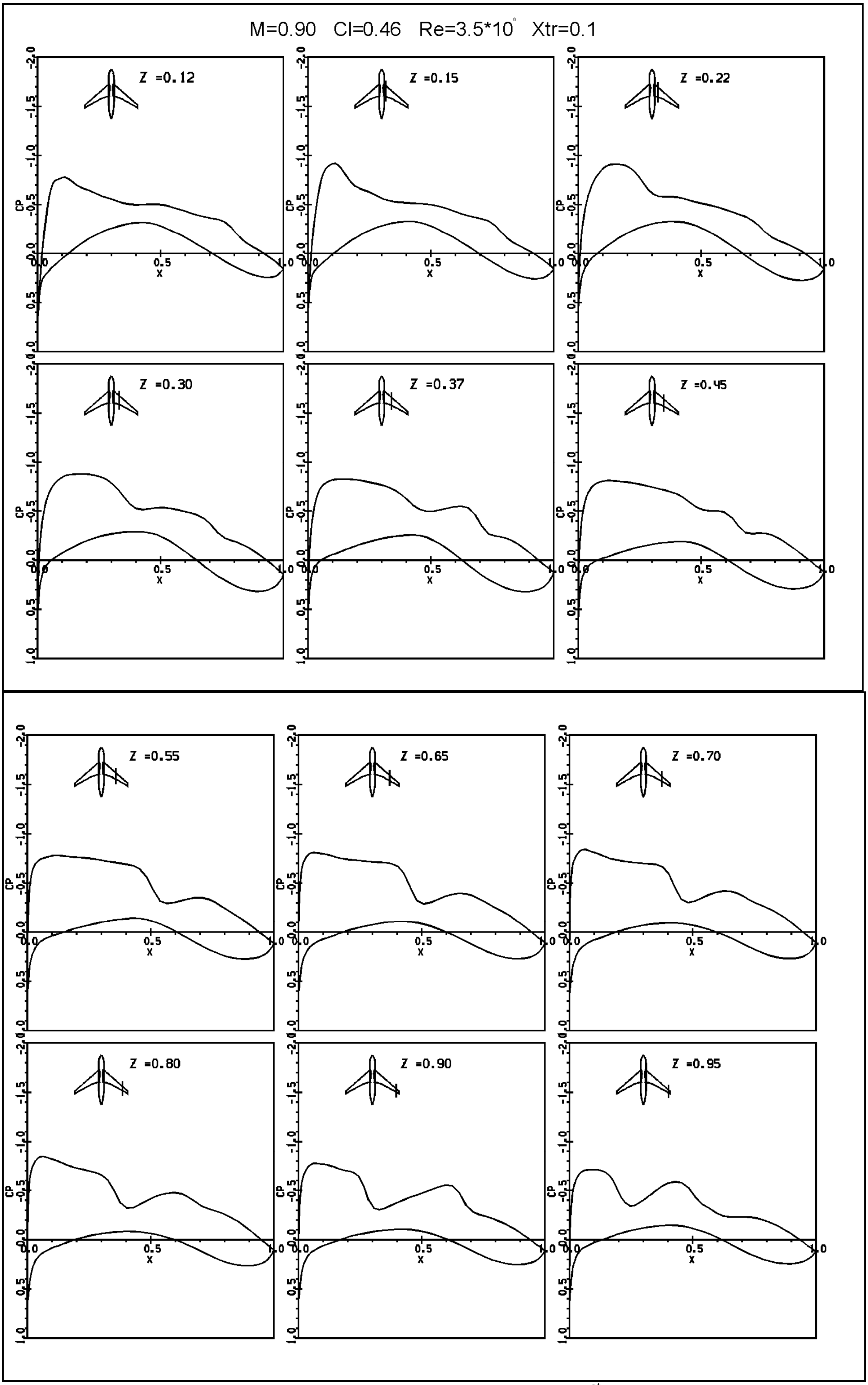

Fig.5 – Computed pressure distribution at 1st design regime

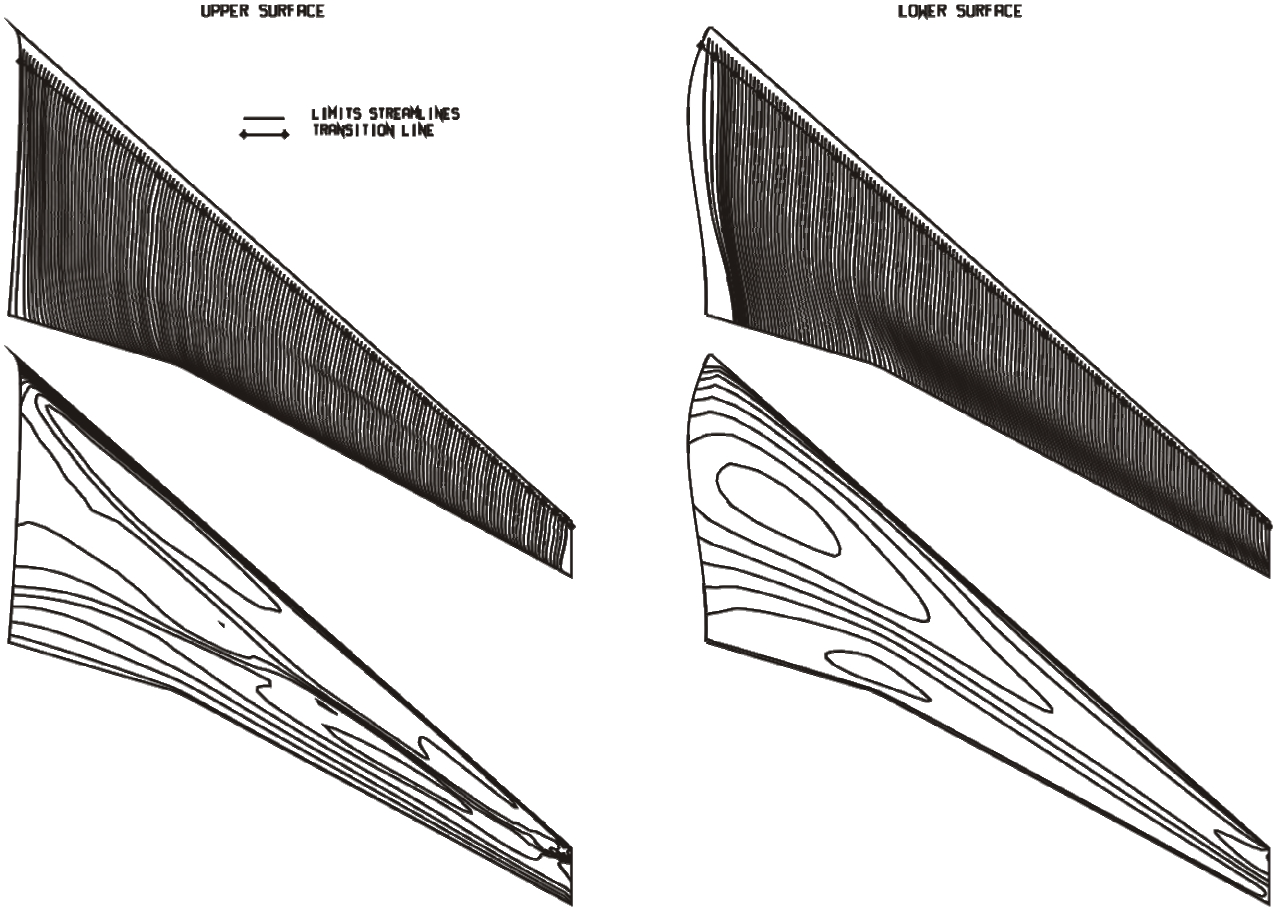

Fig.6 – Surface streamline and pressure isobars at 1st design regime

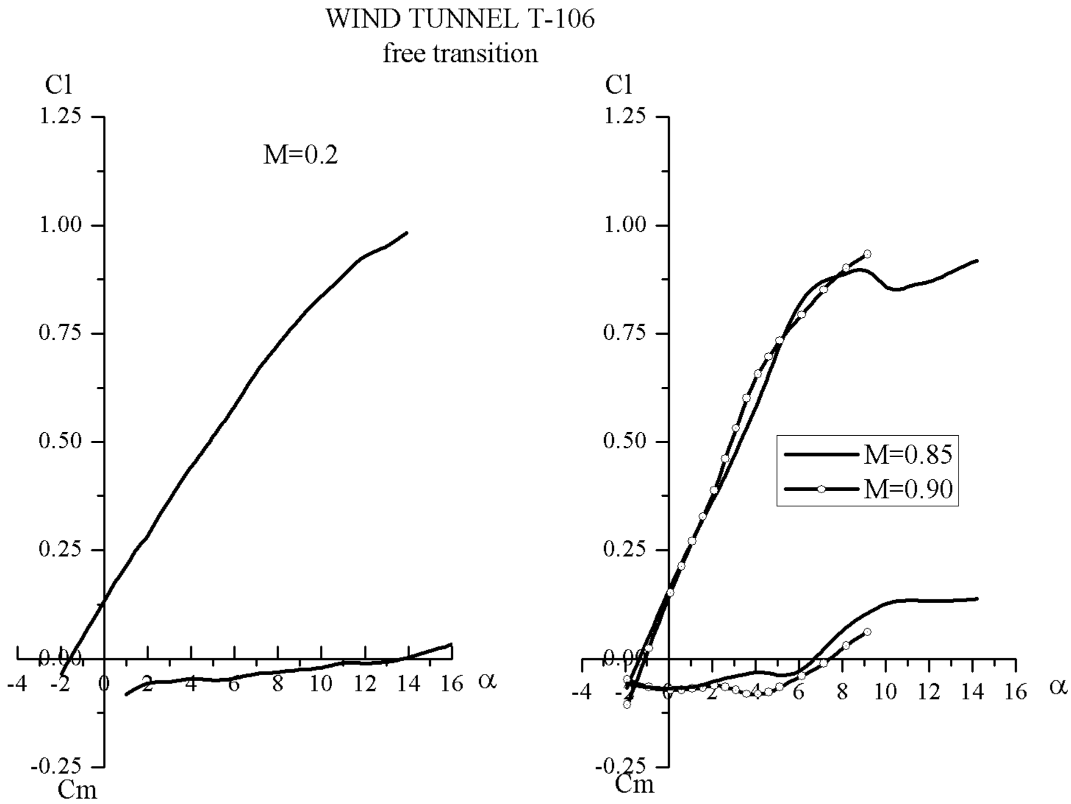

Fig.7 – Lift and pitching moment characteristics

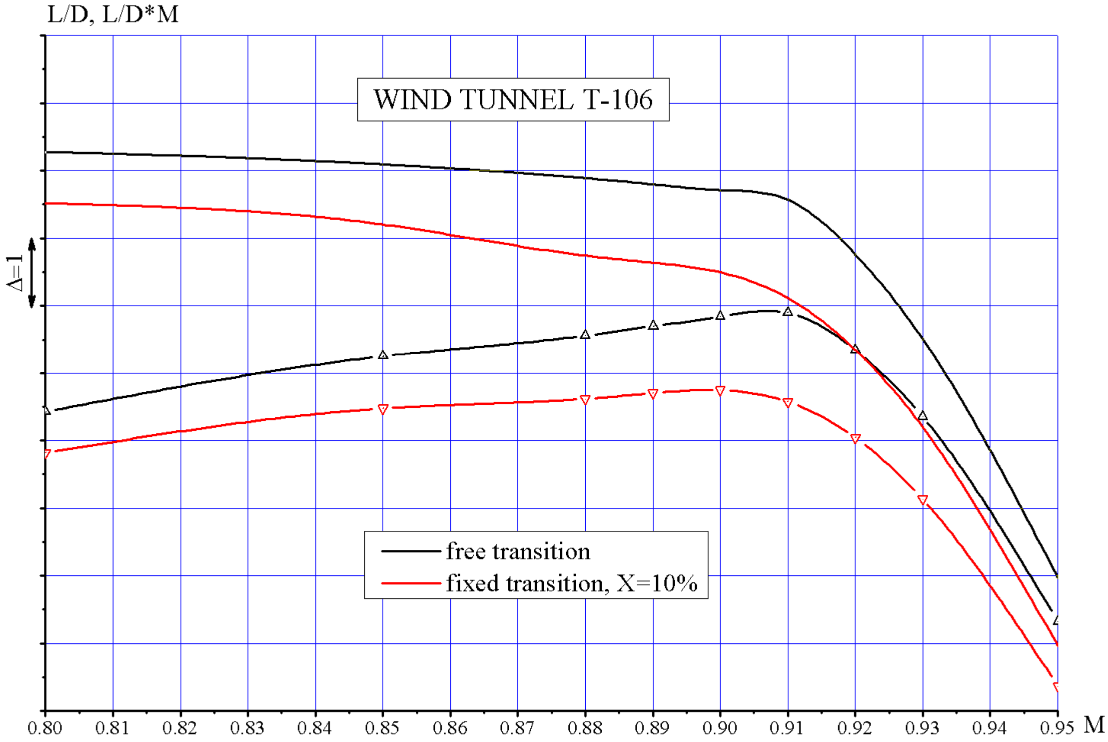

Fig.8 – Experimental L/D and L/D*M dependences vs Mach number