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THE APPLICATION OF THE WING TIP LIFTING SURFACES FOR PRACTICAL AERODYNAMIC.

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Abstract.

A program of research have been completed on studying the aerodynamic characteristics of wings with tip lifting surfaces (winglets, multi-element sails, wingtips of complex planforms). They are based on the methods of experimental and computational aerodynamics which provide better understanding of complex physical essence of the processes of flowing over wing tips with various types of tips and also enables the researchers to determine all possible ways to improve flight characteristics of aircraft. On the basis of the research both on isolated wings and on complete models of the aircrafts of different purposes in a wide range of Mach number (from low subsonic up to supersonic speed) a comparative analysis has been made. The base merits and demerits wing tip lifting surfaces are determined in dependence on the flight regimes : by C_L and M . The results obtained demonstrate great potential possibilities of tip aerodynamic surfaces to practical aerodynamics.

Introduction.

The problem of aerodynamics of wingtip region and wingtip devices of various types arises when studying the ways of increasing aerodynamic efficiency of existing and advanced aircraft and widening their operational capabilities. For this purpose one extensively studies the methods of producing favorable effects on the flowfield about the wing tip and reducing the strength of the trailing vortex with aid of wingtip devices. Among these are winglets, wing tips of complex planform, sails, various modifications of the wingtip side edge as well as wingtip-mounted engines, wingtip turbines, and wingtip blowing. Important advantage of using wingtip devices as additional aerodynamic means is the fact that they can be mounted on existing aircraft without serious wing structure modifications. At the same time in certain cases they can be considered as alternatives to wing extensions made for enhancing the lift-to-drag ratio both in aircraft design and in improving existing aircraft. Although fuel saving is the major objective in studying wingtip devices, there are a number of other problems which can be solved together with their incorporation in design. Primarily it is associated with changes in the flowfield character in the tip vortex because in this case in addition to drag reduction the disturbed velocity field and the circulation distribution in the wing wake are changed. Using of wing tip devices can improve also the characteristics of stability and control of aircraft. Detailed studies of the processes of vortex formation and vortex sheet roll-up can to a large extend be favorable for selecting optimizing geometric parameters of the tip devices for aircraft wings or helicopter rotor blades.

Nevertheless, the effectiveness of wing with various wingtip devices is substantially dependent on flight regime parameters (Mach number M, Reynolds number Re, lift coefficient C_L) as well as on a number of structural factors such as the available flutter-related safety margin, type of the wingtip structure, location of ailerons, fuel stores and so on. Are this should be considered in choosing the type of a wingtip device. Specific requirements, peculiarities of baseline structures and operational characteristics which feature a concrete case can turn out to be decisive in estimating advantages of a wing tip design concept.

Over the last 20-25 years extensive studies of various wingtip devices have been carried out using wind tunnels, flight tests and numerical simulations[1-9]. These investigations were mainly aimed at obtaining induced drag reduction without unfavorable changes in root bending and pitching moments. The results have shown that even slight changes in the planform, spatial location or modifications of the wingtip side edge can have significant influence upon drag and moments on the lifting surface. It should be noted that all these approaches have their advantages but at the same time are responsive and not always well-adjustable to changes in flight regime parameters, also, they are sometimes not effective enough. Therefore, most of the proposed wing tip structural concepts remained unrealized, some of them are in preliminary design stage and only a few of them have found industrial application in actual aircraft designs. Considered presently as the most promising is the following concept of wingtip aerodynamic surfaces : winglets, wing tips of complex planforms, multi-element sails.

Study methodology.

The study of the effectiveness of wingtip devices and their influence on aircraft aerodynamic characteristics is intimately connected with the study of the flow over the wingtip region. An understanding of the nature of the flow about a wing tip is particular necessity in systematic practical design of wingtip devices with taking into account their potentialities and limitations. The purpose of the investigations carried out is the development of the methodology for designing wingtip devices like tip lifting surface : winglets, wing tips of complex planforms, multi-element sails with taking into consideration geometric features of a baseline wing, flight regime (Mach and Reynolds numbers) at the presence of structural and aerodynamic limitations of various kinds. This methodology is to include :

- selection of the type of the tip aerodynamic surface based on its advantages and disadvantages with accounting for requirements imposed;
- determination of optimum geometric parameters of a selected type of the wingtip device to provide as full as possible realization of its effectiveness on a specified baseline wing.

The main idea of wing tip devices considered here is as follows. In the near-tip flow region where local angles of attack are more than the wing angle of attack, one or several additional aerodynamic surfaces of small relative area are mounted at different angles to the wing surface. They are mounted in such a manner that they can interact with the wing-produced vortex structure in order to reduce induced drag. The problem of designing such additional wing tip devices working in intensive and substantially nonuniform velocity field is a quite complex one which is often as difficult as that of designing the wing itself. Unfortunately, the reduction of induced drag obtainable with the aid of an additional aerodynamic surface can be accompanied by increasing other drag components and adversely changing such important characteristics as nose-down pitching moment and wing root bending moment, etc.

For this problem to be studied more rationally and comprehensively, one should use experimental methods along with of computational fluid dynamics. Major parametric experimental investigations on the effectiveness of wingtip devices of various types were conducted in the TsAGI wind tunnels at low subsonic, transonic and low supersonic speeds on isolated wing models with removable outboard wing portions.

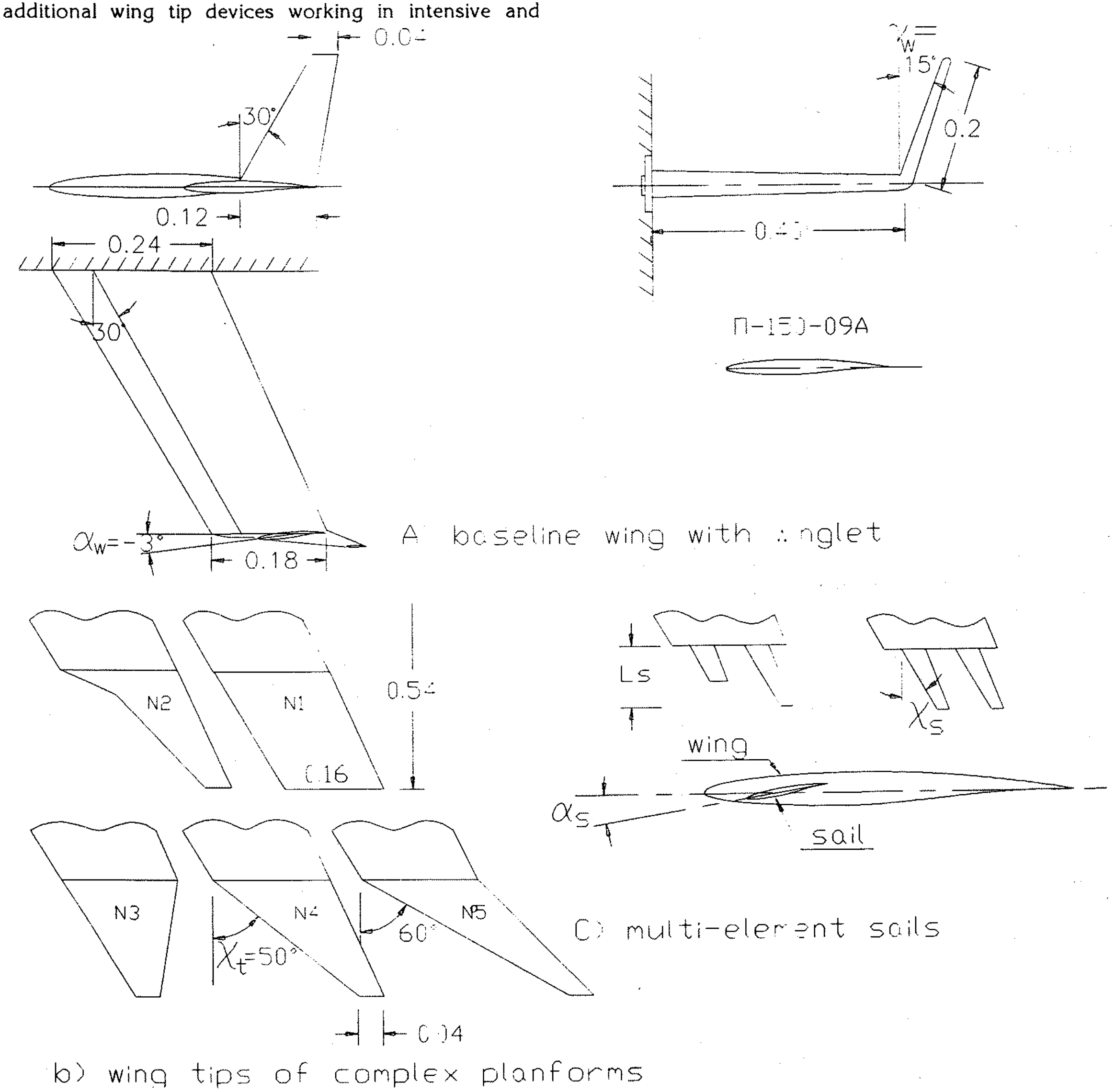

Fig. 1 Wing planform and various wing tip devices (model configurations).

One of such wing models shown in Fig.1. The Reynolds number range based on the mean aerodynamic chord was between 1-3 million. It is to be noted that in so doing the local Reynolds numbers based on the wingtip device chord (especially in the case of the sails) may be significantly less that a million. Because of this one should handle the wind-tunnel test results with care considering that at these low Reynolds numbers extensive laminar flow regions can occur at low angles of attack and premature flow separation can occur even at moderate lift coefficients, which does not take place under full-scale flow conditions. Investigations of wingtip devices of various types on the same wing models have enabled not only revealing their aerodynamic features but conducting the comparative analysis of their effectiveness under equivalent conditions over wide ranges of attack angles and Mach numbers. Test on complete models of current and advanced aircraft have confirmed the conclusions made from the isolated-wing tests and have shown the effectiveness of using wingtip lifting surfaces of various types on actual aircraft.

Results and Discussion.

Winglets.

The issues associated with studying and developing the winglets of small relative area were considered[10] as applied to existing and advanced passenger and transport aircraft with high-aspect-ratio wings. The effectiveness of winglets depends on properly selecting such their geometric parameters as relative area, planforms, twist, airfoil section, position and orientation relative to the wing (cant angle γ_{wl}, setting angle α_{wl}, location relative to the wing tip, chord position, etc.) as well as on selecting the shape of the near-tip wing portion adjacent to the winglet.

But as studies[11,12] have shown winglets can make significant influence on the aerodynamics of wing with relatively small aspect ratios inherent in modern maneuverable aircraft. The reduction assumed in induced drag is to only depend on cant angle and winglet relative span. Theoretically, the reduction in induced drag is to be provided both for low-aspect-ratio and high-aspect-ratio wings. In actual practice the situation is much more complicated because the real flow over a highly swept and tapered low-aspect-ratio wing is characterized by more developed three-dimensional vortex and separated-flow structures. Also, these flows can be substantially affected by compressibility effects at trans- and supersonic flight speeds. The features of winglet-produced effects at trans- and low supersonic speeds are illustrated in Fig.2 by comparing erodynamic characteristic of the wing without winglets and wing having the one- sided upper or lower winglet mounted at cant angle (angle between the winglet datum plane and vertical plane) of γ_{wl} =15°/175° and a setting angle (angle between the winglet root chord and the incoming flow direction) of α_{wl}=var. Tests have shown that the relative lift-to-drag (K=L/D) increment $\Delta \overline{K}=(K_{max,wl}-K_{max})/K_{max}$ varies little with Mach number as M<0.9 and remains positive in supercritical flow regime.The correlation of C_L versus α shows that over the Mach number range under consideration, M=0.6-1.25, the installation of winglets results in a slight increase in the maximum lift C_L max and in increasing in the lift-curve slope C_L^{α} as compared to the baseline wing. As computations with Euler equations[13] (Figs.3) show, this relative decrease in lifting capability of a wingletted wing at supersonic Mach numbers as compared to subsonic speeds is caused by the fact that at M>1. the winglet influence zone extension in spanwise direction shrinks significantly. As a consequence, the additional load on the outboard wing portion falls down substantially. Thus, one can see in Fig.3 that at M=0.6 the winglet-produced increase in sectional force coefficient Cn,sec is observed already beginning with $\bar{z}$ =0.5 whereas at M=1.2 this effect only comes into action at $\bar{z}$ =0.8 . A similar pattern is also observed on pressure distribution curves .

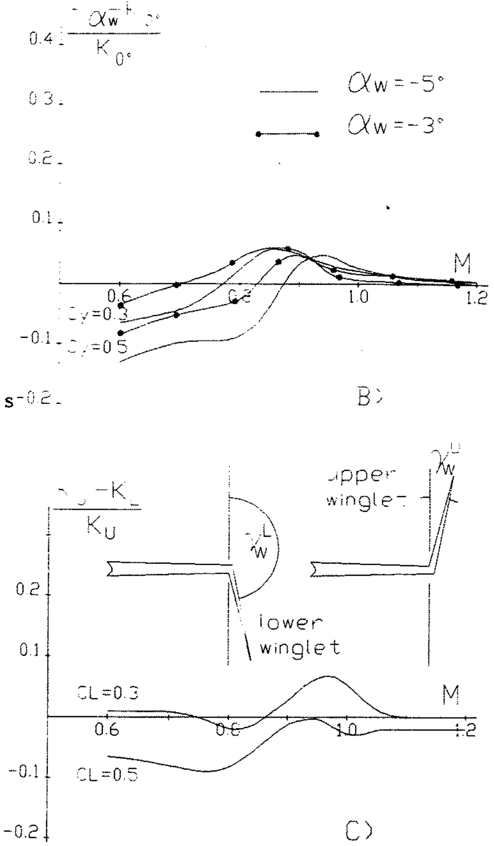

Fig.2 Effect of winglet parameters on lift-drag ratio (K=L/D) of swept wing in dependence on Mach numbers.

The important parameter defining the effectiveness of winglets is their setting angle α_{lw}. The (L/D) versus α_{wl} curve is substantially non-linear. In a supercritical flow regime the significance of the winglet setting angle increases and larger negative α_{wl} values become advisable, the optimum with respect α_{wl} being more gentle as setting angle becomes more

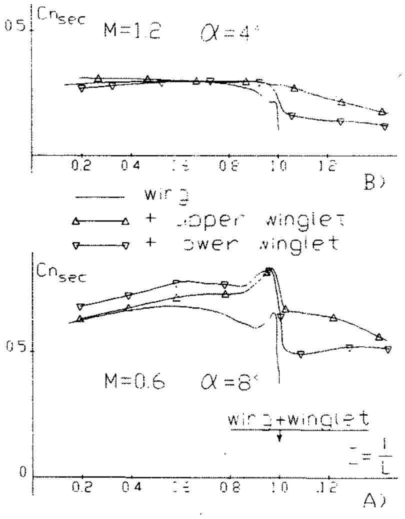

Fig.3 Comparison of spanwise load distributions between isolated wing and wing with winglets (upper/lower) for subsonic and supersonic Mach numbers.

negative. This trend is also valid for actual aircraft layouts, where it often turns out that even more negative α_{wl} values are advisable than that obtained on the half-wing model tested.

The investigations performed has shown that from both the aerodynamic (ΔKmax) and structural (ΔC_b max) viewpoint the upper winglets are somewhat preferable to the lower ones, especially with increasing Mach numbers at modest lift coefficients. But for some aircraft general layouts with their inherent operational features the use of lower winglets or the combination of the upper and lower winglets can be more advisable.

An increase in the load on the near-tip wing portion and the presence of normal forces on the winglet lead to increasing the wing bending moment throughout the wing sections including the near root ones. An analysis of experimental data shows that if at subsonic speeds the upper winglets do not alter substantially the bending moment C_b at high angles of attack, at supersonic speeds they yield an increment of the bending moment practically over the entire angle-of-attack range just as a conventional wing extension does. This is attributable to the decrease at supersonic speeds of nonlinear effects associated with more earlier flow separation at high angles of attack on the near-end wing portions highly loaded due to the presence of upper winglets. As a result, the maximum of the bending moment versus lift coefficient curve, $C_b(C_L)$, the presence of which was revealed by N.A.Chicherov in wind-tunnel experiments at subsonic flow speeds[10], shifts to greater lift coefficient values. The presence of that maximum and the lift coefficient value at which it occurs are of importance when estimating load in structural design. stability at $M>1$ and from the need for enhancing lifting capability at transonic

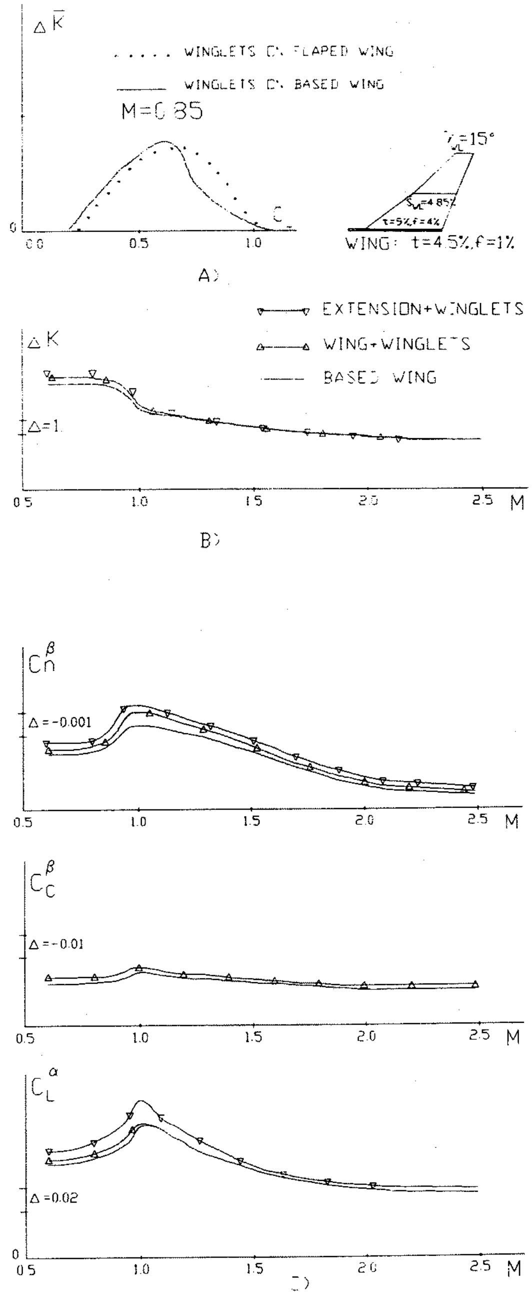

Fig. 4 Winglet effect on aerodynamic characteristics for complete model maneuverable aircraft.

maneuvering and for improving lift-to-drag ratio to increase ferry range when cruising at high subsonic Mach numbers. In so Necessity of designing winglets for maneuverable including supersonic aircraft stemmed from the problem of ensuring their sufficient directional doing, the winglet airfoil section and sweep angle (χ>60) are selected with accounting for the peculiarities of flight of such an aircraft : it is to have enhanced lift-to-drag ratio at high subsonic speeds and low drag at modest lift coefficients in accelerating with supersonic Mach numbers. Going from supercritical to thin airfoil sections world only slightly reduce the total aircraft wave drag due to a small winglet area, but can impair transonic aerodynamic characteristics at near-maximum lift-to-drag ratio due to emerging premature flow separation.

Experimental studies have shown (fig.4) that the installation of winglets results in increasing lift-to-drag ratio in the vicinity of its maximum by 6-7% relative to the model L/D maximum. The installation of winglets increases the C_{Do} value mainly at supersonic Mach numbers, on average, by ΔC_{Do}=0.002. This leads to decreasing the increment of maximum lift-to-drag ratio which becomes equal to zero at M=1.5, thereafter the lift-to-drag ratio of wingletted wing becomes little different from that of the isolated wing (Δ(L/D)max=-0.1 at M>1.5, fig.4b).

It should be notes that as the tests of complete aircraft model have shown, at supersonic speeds the lifting capability of a wingletted wing (fig.4c) are little different from those of the wing with no winglets, that is, the high winglet effectiveness ones holds up to M>1. The most important issue on these investigations was a study of changing lateral characteristics (fig.4c). As would be expected, the installation of winglets has led to increasing the directional stability coefficient Cn throughout the speed range : ΔCn^{β} =-0.0005 at M<1 and ΔCn^{β}=-0.0004 at M>1, that is, the directional stability of the wingletted aircraft increases. The increment of the side force coefficient Cc decreases from ΔCc^{β}=0.002 at M<1 to Cc^{β}=0.001 at supersonic Mach numbers.

Wing tips of complex planforms.

Although winglets are effective means of increasing aircraft lift-to-drag ratio. However their use is accompanied by an increase in aircraft weight, nose-down pitching moment, and wing root bending moment. Also, the height of these winglets, which are installed at near-right angle to the wing plane, are rather large (on the order of a tip wing chord length), which sometimes makes their mounting practically impossible or questionable as, for example, on a helicopter rotor blades or on a variable-sweep wings. In this connection the question arises of whether it is possible to effectively use of wing tip of complex planforms which can be considered as a simple means of modification of the shape of the wing tip yielding not only a total drag reduction but also a decrease in wing root bending moment. Such wingtip devices are a modification of a wing in its baseline plane by changing sweep and taper ratio, shaping and twisting its near-end portion on order of wing chord in length[14,15].

Considered below are the main peculiarities of the flow over the wing tips of complex planforms and the causes of improving wing aerodynamic efficiency based on the analysis of some computational and experimental results for the wingtip lifting surfaces presented in Fig.1b . A decrease in the exposed wing area, clearly, leads to a decrease in friction drag, which provides the effectiveness of wing tip with complex planforms even at low lift coefficients, including C_L =0. This is an important feature of wing tip surface of such type, for example, as compared to winglets which are only effective when the induced drag reduction is in excess of form drag penalties due to additional aerodynamic surface area. According to a classical wing theory, an increase in the wing geometric aspect ratio due to tip devices of the type under consideration leads to a decrease in induced drag due to redistribution of circulation across the lifting surface span. Depicted in Fig.5 is the experimental (L/D)max versus AR_{geo} curve which illustrates the variations of maximum wing aerodynamic efficiency as a function of wing geometric aspect ratio (AR_{geo}= 5.14, 6.28, 7.14) when increasing baseline wing span. Also shown here is an experimental point for a wing with the wing tip of complex planform. One see that wingtip device installed on a swept wing gives the some result as an increase in effective aspect ratio by ΔAR_{eff}=2.0 (as compared to wing with AR=7.14), whereas an increase in geometric aspect ratio is only ΔAR_{geo}=0.9 .

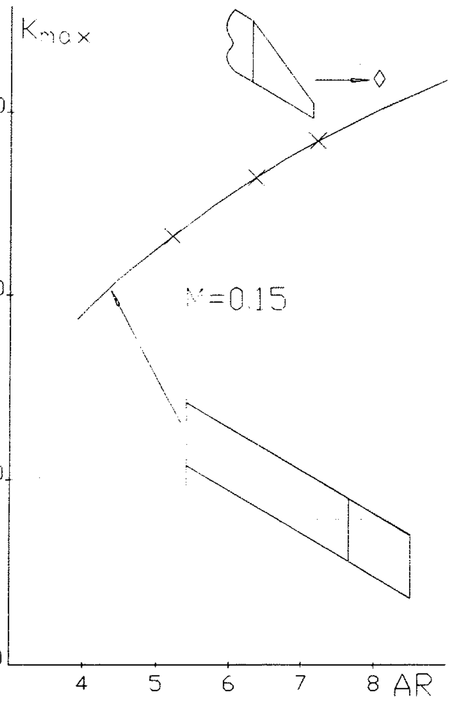

Fig. 5 Effect of the wing tips of complex planforms on lift-drag ratio of swept wing, χ=30°.

The third factor of no less importance, which influence the effectiveness of wing tips of complex planforms is a change in the character of the local flow field over the near-end wing portion. The peculiarities of this flowfield are commonly not accounted for within a framework of the classic wing theory. The change in the character of the flow over the wing tip results in a very substantial pressure redistribution across wingtip sections, which is

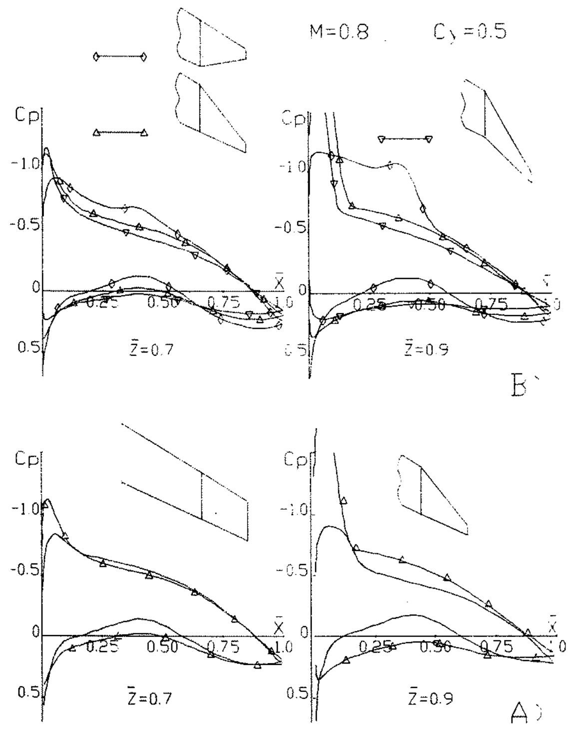

Fig. 6 Chordwise pressure distributions for various wing planform tips.

indicative of a significant effect on integrated aerodynamic characteristics. In practice the more important is a pressure redistribution in the sections of wing tip due to intensive lateral overflow caused by their high sweepback angles and very low taper ratios. Fig.6 shows the pressure distribution in the sections $\bar{Z}$ =0.7, 0.9 of the wing with tips of complex planforms differing in effective sweep. Pressure distribution curves differ more profoundly in the vicinity of the stagnation point on the wing lower surface. This difference manifests itself in a significant pressure drop in this region on the swept wing tip. Because this flow region makes the most significant influence upon the pressure drag curve run (Fig.6), its breakdown (or recovery) leads to abruptly increasing (decreasing) pressure drag in a wing section as the sweep angle of the wing tip device increases. Other additional source of reducing the sectional drag of a wingtip device can be an increase in a suction peak on the upper surface of the airfoil nose as the sweep angle of wing tips increases. But the realization of this mechanism under the conditions of actual viscous compressible flow is limited.

The fact that the effectiveness of wing tips of complex planforms is defined not only by increasing wing geometric aspect ratio due to decreasing their area is confirmed by comparison of computational and experimental data. According to computed results, an increase in geometric aspect ratio due to the application of tip lifting surfaces leads to a corresponding decrease in induced drag, whereas wind-tunnel tests have shows that the shape of wing tips also affects wing aerodynamic characteristics at the same geometric aspect ratio and area.

Unfavorable changes in flow nature, especially with increasing Mach number due to modifications of wing tips' shape, may result (in spite of increasing the geometric aspect ratio and decreasing induced drag) in a growth of profile drag as a result of increased aerodynamic loading in the sections of narrow-chord wing tips and the occurrence of premature separation and shocks in this zone of the wing, which is especially characteristic of wind tunnel tests at low Reynolds numbers. This trend under real flight conditions is expected to be significantly less pronounced.

The gain in induced drag due to application of the swept wing tips slightly grows with increasing wing tips' sweep angle. The observed abrupt growth of values of Cn,sec in sections of the wing tips also substantially depend on the tips' leading edge sweep angle, these values being minimum at χ_t =30° . Fig.7 show experimental relationships between the lift-to-drag ratio of the wing with the swept tips and lift coefficient at equal Mach numbers (subcritical M=0.6 and supercritical M=0.85). At subcritical Mach numbers and $C_L < C_{L\,Kmax}$, when there are no wave drag and flow separation on the wing, the main contribution to increasing the lift-to-drag ratio is generally due to a decrease in induced drag and friction drag with decreasing the wing area. When values of C_L grow ($C_L > C_{L\,Kmax}$), local flow separations occurs on the upper surface of the wing tips with narrow chords, which leads to a significant drop in their efficiency. To the largest decree, it manifests itself on wing tip N2 with a root strake and narrower chords. The use of wing tips with greater sweep compared to the main wing (Nos.4,5) increases the Mach number critical value owing to an increase in the effective sweep of the lifting system. A drop in efficiency of wing tip N3 with the leading edge being the extension of the wing leading edge, in supercritical regime, are related, as computations show, to stronger shocks (see,Fig.6). As sweep grows, the wing tips retain their efficiency even at supercritical Mach numbers, when on the main wing occur shocks. However, at value of $C_L > C_L$Kmax and with increasing Mach numbers one can see a drop in wing tips' efficiency (Fig.7), when their sweep exceeds a some optimum value (50°<χ_t <60°) in spite of the fact that the local values of Cn,sec in the wing tip's sections vary little. The installation of wing tips of complex planforms, as shown by computations and experiments, results not only in increasing the lift-to-drag ratio, but also in decreasing the root bending moment compared to a usual wing tip, as well as in increasing the nose-up pitching moment.

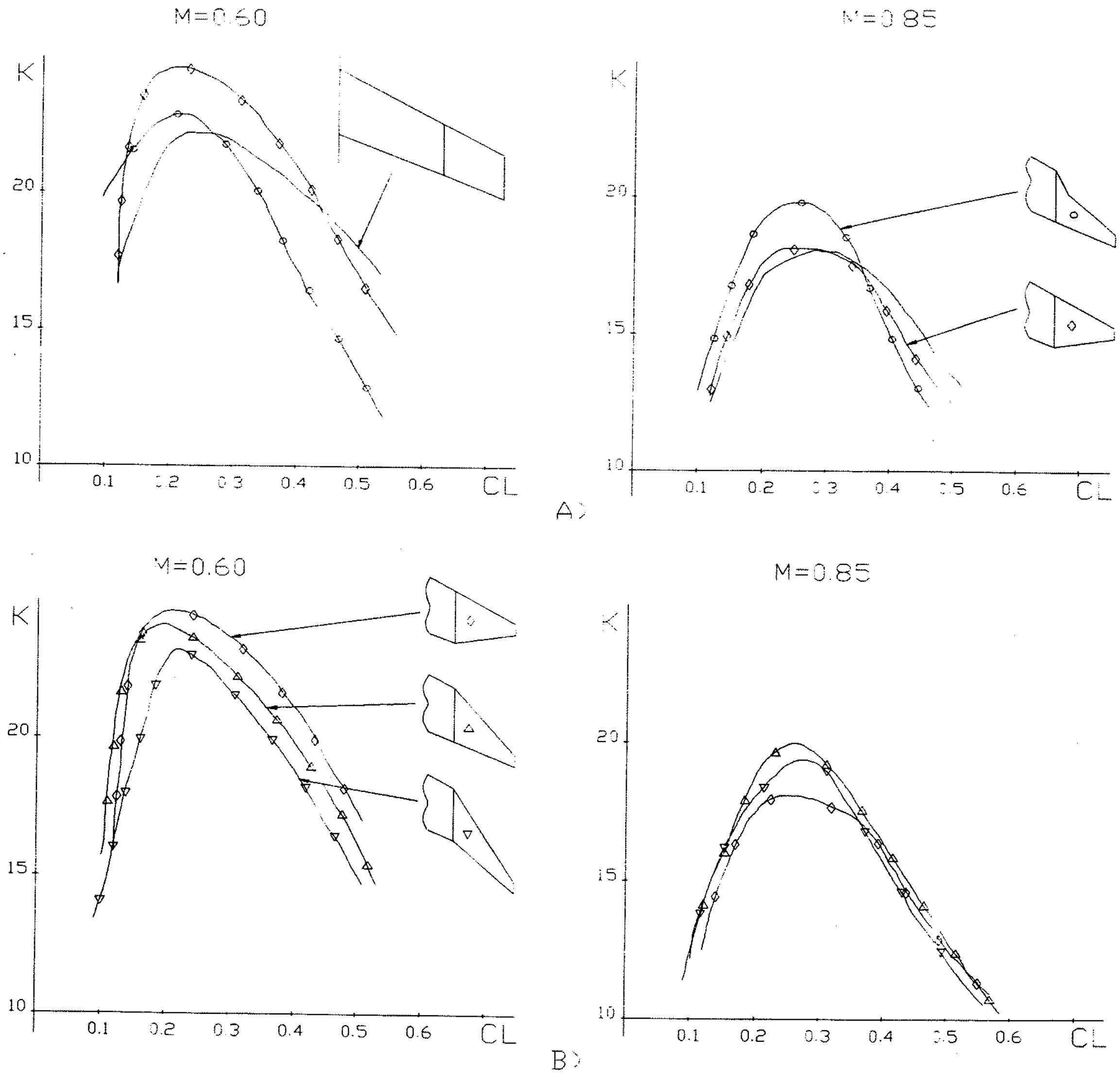

Fig. 7 **Dependence the lift-drag ratio for various planform tip on Mach number.**

Multi-element sails.

Alongside winglets and wing tips of complex planforms, there are other wingtip devices of aerodynamic surfaces' type for decreasing induced drag. Such promising devices requiring detailed studies are multi-element wingtip devices, so-called sails, which constitute a number of small aerodynamic surfaces installed at the wing's tip chord . Such devices may be considered as one of branches of the concept to use additional wing tip lifting surfaces for a better adaptation of wing designs to various flight regimes. The choice of sails' parameters is even more complex, since the number of components and their relative locations is significantly greater in this case[16].

Variations in the lift-to-drag ratio and lifting capacity due to sails are accompanied by variations in the bending moment C_b along the wing span. Therefore, when using any type of wingtip devices it is necessary to allow for increasing not only the wing root bending moment, but also the loading on attachment points of the wingtip elements. The choice of wingtip devices' type must be determined by thestrength margin of the baseline wing and by limits on the overall dimension of the aircraft. Shown in Fig.8 are variations of the bending moment increment for various multi-element wing configurations. Using sails results in increasing the wing root bending moment in proportion to their number and span.

However, this increment is substantially less than that of the baseline wing with the same span. An analysis of aerodynamic characteristics shows that already for two-element wingtip surfaces the lift-to-drag of such a lifting system exceeds that of the baseline wing of the same span, whereas the bending moment increment is significantly lower. As this takes place, beginning with a some lift value the growth of the bending moment of the wing with sails practically ceases, which associated with the onset of flow

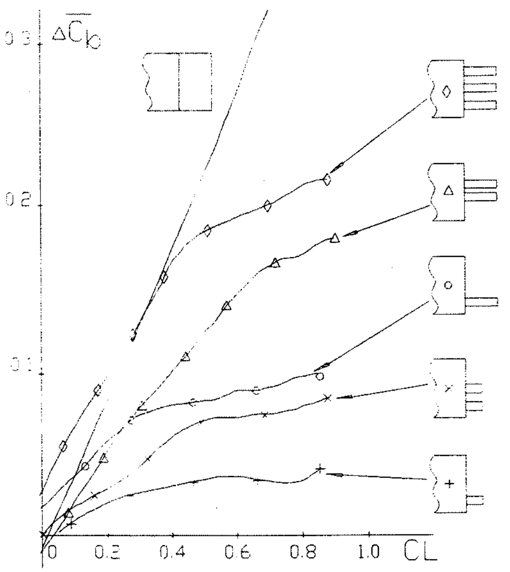

Fig.8 Comparison of bending moment coefficient for a various "wing+sails" configurations.

separation on wingtip lifting surfaces due to their narrow chords and play an important role in structural design of such lifting system.

As a criterion of the efficiency of wing tip devices one can select a parameter ε equal to an increment in the lift-to-drag ratio divided by an increment in bending moment for specified value of the lift coefficient. A comparison of multi-element sails at various lift coefficient values using the ε- criterion is presented in Fig.9. It can be seen that for a one-element sail the coefficient ε exceeds that of baseline wing, the same is true for K, only for a very narrow range of C_L, which is determined mainly by the setting angle α_s. With rising the negative values of α_s the value of ε_{max} shifts to a region of high lift coefficients, it also decreases with increasing the span of the sails. As this takes place, the optimum spans of sails, regardless of their number, lie in a region of (0.3-0.4) wing tip chord. The best results from the viewpoint of the parameter ε and the effective C_L-region refer to the wing with two-element sails.

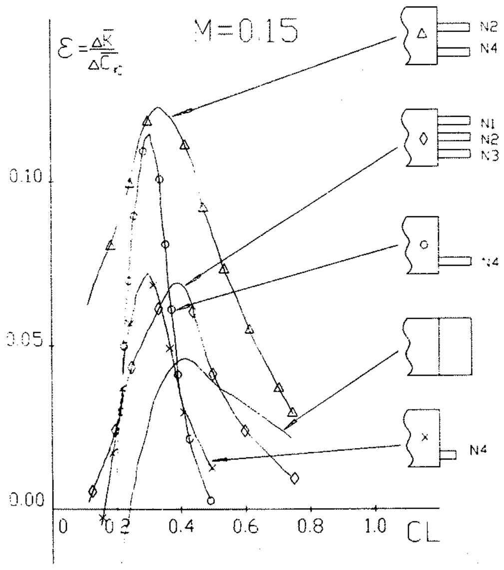

Fig. 9 Comparison of efficiency coefficient ε for a various "wing+sails" configurations.

As mentioned above, the most important parameter of sails is the setting angle α_s of each individual element. There is some optimum setting

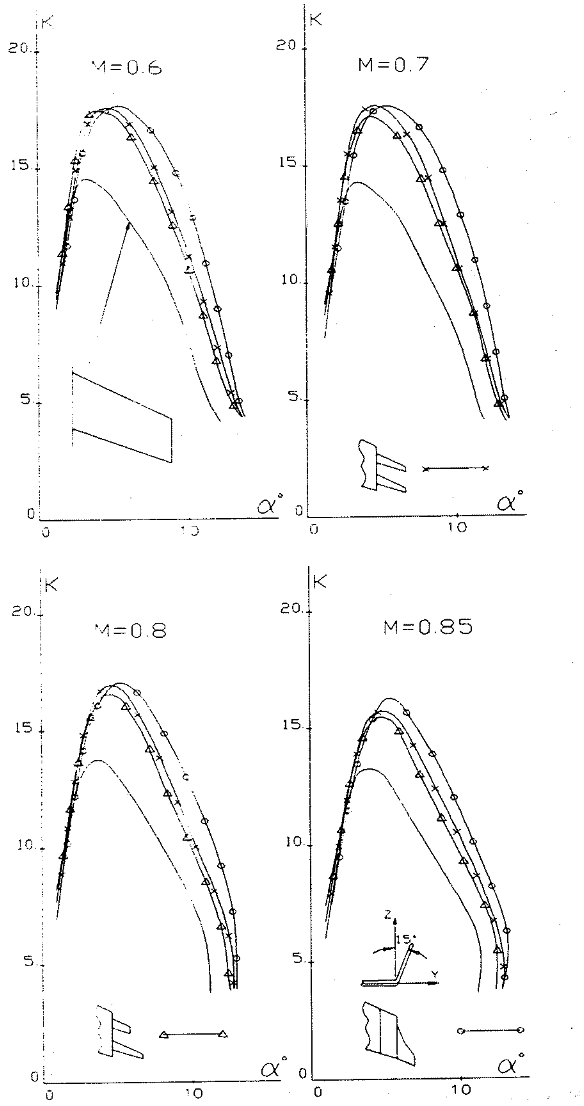

Fig. 10 Comparison of efficiency of the wing with winglets and "wing+sails" configuration.

region for each sail, which permit one to choose greater negative values of α_s,insignificantly losing in ΔK, but providing more favorable flow about the wingtip element and decreased loading on it. It should be noted that with increasing sweep the optimum setting angle of the sail shifts in the negative direction. The same is true with increasing the Mach number of the incoming flow. Thus, with emergence of increasingly strong disturbances in flow the sail element should be installed at a greater negative angle, but these value are limited due to an adverse effect on induced drag. However, in the case of sails with high negative angles α_s there will be a probability of flow separation on the element's lower surface at low angles of attack of the wing. Under these conditions the drag of the tip devices may increase, but with increasing angles of attack attached flow is restored with a corresponding decrease in drag. It look advantageous to use adaptive sails with variable setting angle (and cant angle) in flight, which should permit one to significantly expand the

It is of practical interest to compare a wing with sails not only with baseline wing, but also with a wing of equal span and with winglets. Chosen for comparison was the optimum winglets with a setting angle of α_{wl}=-3° and a cant angle of γ_{wl}=15° . In this case the span of the wing with winglets is somewhat greater than that of wing with sails. As can be seen in Fig.10 such winglets provide approximately the same level (in fact, slightly greater) of the increment of the maximum lift-to-drag as sails do, and significantly greater efficiency at large C_L ($C_L > C_{L\,Kmax}$), which is associated with separation effects on narrow-chord elements. But using adaptive (with variable setting angle) sails, their efficiency may approach that of winglets over the

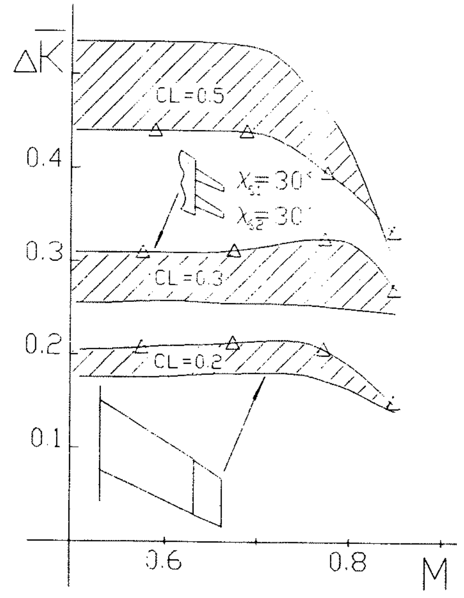

Fig. 11 Comparison of the big wing and "wing+sails " configuration in dependence from Mach number.

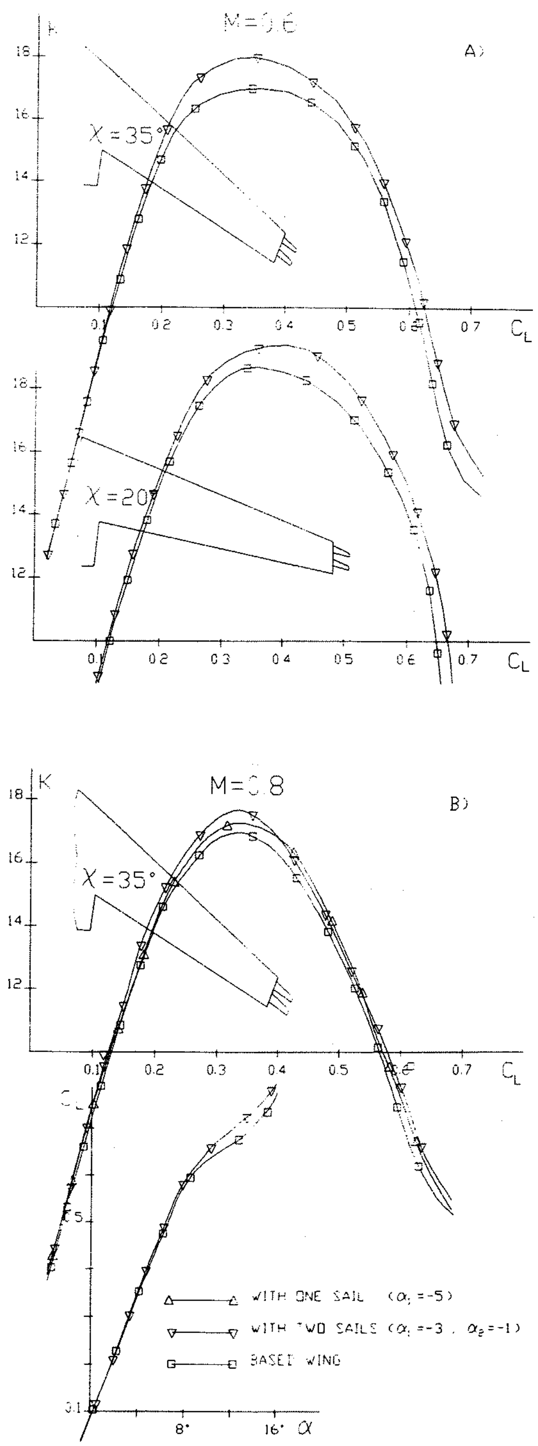

Fig. 12 Aerodynamic characteristics of the aircraft's wing with variable sweep.

entire range of C_L. It should be noted that winglets give not only greater derivative $dC_L/d\alpha$ and a greater C_L max, but also a greater increment in the bending moment as well as in the nose-down pitching moment.

Fig. 11 represents a comparison between a wing with multi-element sails and a wing of the same span respect to efficiency. For example, at subcritical Mach numbers the maximum lift-to-drag ratio of the wing with two- element swept sails ($\chi_{s1}=30°$, $\alpha_{s1}=-5°$; $\chi_{s2}=30°$, $\alpha_{s2}=-3°$) is somewhat greater than that of the wing of equal span ($\Delta K=0.5$-0.7). Such configuration has slightly less values of derivative $dC_L/d\alpha$ and C_L max, as well as significantly less the root bending moment and the nose-down pitching moment, which is a positive factor for swept wings. However, at high C_L-value ($C_L > C_L$ Kmax) the wing with sails begins to give way to the wing of equal span with respect to efficiency. At supercritical Mach numbers the lift-to-drag ratios of the wing with sails and wing of the same span become practically equal.

Practical application of the sails is considered on example of the aircraft with variable sweep wing. Characteristic peculiarity of given aircraft's type appear wide range of the wing console swept from take-off configuration ($\chi=20°$) to supersonic flight regime ($\chi=65°$). Cruise flight of similar aircraft is carried out in configuration with .....value of the wing sweep about $\chi=35°$ for transonic Mach numbers. The principal problem for such aircraft is a necessity of rise lift-to-drag for subsonic and transonic regimes without .loss. in drag for supersonic velocities at restriction size on ground. Winglet installation in this case is not enable.

On fig. 12 wing model scheme and some results of the experimental investigation sail lifting system are presented. Area of every sail compose about 0.25% of wing area. Mounting two elements on aircraft wing lead to essential increase lift-to-drag in cruise configuration (ΔKmax=1-1.1, for M=0.6) and accompany by rise wing lifting capability. Reduction of sweep angle before to 20° bring decrease (lowering) (ΔKmax.=0.6), although on this take place displacement location region of Kmax. on sense lift coefficient with CL=0.35 (without sails) to CL=0.4 (with sails). Comparison lift-to-drag coefficients for C=0.4 show (demonstrate) that sail's effect in this case is preserved enough high ($\Delta K=0.8$-1.0).

These results confirm (prove) data receipted on isolated wings, and demonstrate big potential possibilities sail's concept.

Comparative analysis of the efficiency of wingtip lifting surfaces at various types.

The results of computational and experimental investigations presented above, as well as of other studies, show a great potential of aerodynamic wingtip devices for increasing efficiency of today's and future aircraft. Their usage on a number of production and prototype aircraft confirms these results. However, the question about practical expediency of the usage of wingtip devices (instead of using a extension of the wing) remains open since besides the aerodynamic efficiency of such devices a number of other additional factors should be taken into account, which may significantly affect the choice of a wingtip configuration.

After the establishment of economical and technological expediency of the use of aerodynamic wingtip devices for functional efficiency enhancement, it is necessary to conduct a comparative analysis of

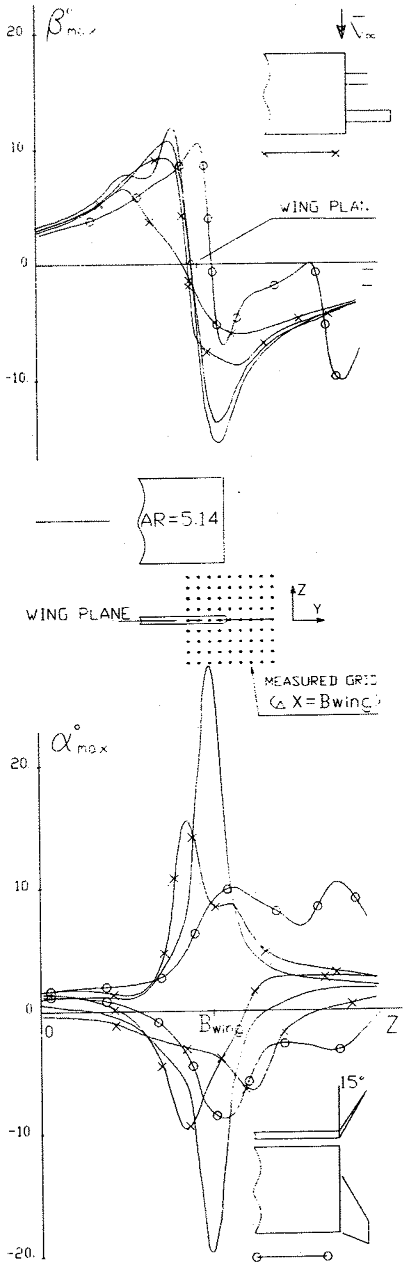

Fig. 13 Effect of wing tip lifting surface on vortex velocity distributions, ΔX=Bwing,

$$\alpha=\mathrm{arctg}\left(\frac{V_z}{V_\infty}\right),\ \beta=\mathrm{arctg}\left(\frac{V_y}{V_\infty}\right).$$

various devices for identification the optimum one under specified conditions. Undoubtedly, if a tip device can be used for several purposes, it can strongly influence its final efficiency.

One of the important problems in studying wingtip devices is prediction and analysis of variation in the flowfield in the region of the end vortex (or a vortex system) due to the installation of wingtip devices of various types, ensure which an increase in the lift-to-drag ratio. Wingtip lifting surfaces significantly affect the intensity and structure of the vortex wake behind an aircraft owing to the splitting the end vortex into a system of several vortices, their mutual interference and earlier dissipation. The most effective devices from the standpoint of decreasing vertical and horizontal flow angularities at various distances behind the wing are winglets and sails (Fig.13).

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