United States Patent [19]

Rethorst

[11] **3,712,564**

[45] **Jan. 23, 1973**

[54] SLOTTED DIFFUSER SYSTEM FOR REDUCING AIRCRAFT INDUCED DRAG

[76] Inventor: **Scott C. Rethorst,** 1661 Lombardy Road, Pasadena, Calif. 91106

[22] Filed: **Nov. 13, 1970**

[21] Appl. No.: **89,415**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 792,872, Jan. 21, 1969, abandoned.

[52] **U.S. Cl.** **244/41**

[51] **Int. Cl.** **B64c 3/00**

[58] **Field of Search** 244/41, 40

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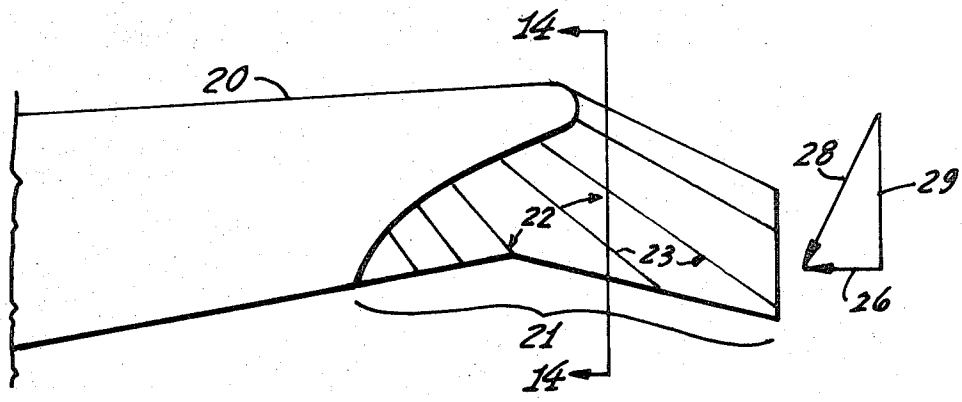
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Primary Examiner—Milton Buchler
Assistant Examiner—Carl A. Rutledge
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[57] **ABSTRACT**

A wing assembly for increasing lift and reducing drag is disclosed comprising (1) an inboard conventional primary wing panel, and (2) an outboard secondary wing panel which is aft-swept and comprised of a cascade of airfoil elements. The inboard panel is provided with a constant lift distribution which is dropped sharply at the knee or juncture with the outer panel, shedding a substantially concentrated vortex at the knee rather than at the wing tip. The sweep of the outer panel deflects the flow carrying this vorticity outboard, and its cascade airfoil elements then operate in the upflow outboard thereof. The cascade elements of the outer panel are stacked vertically above to the rear, so that the vorticity shed from each element generates a spanwash providing an incremental lift and thrust on the next element aft and above, which, in turn, because of its sweep deflects the vorticity underneath outboard, providing a greater effective span. The cascade splits the vortex into a vertical stack of vortex sheets, which laminate into an expanded size, slowly turning vortex core. The energy and corresponding induced drag of the vortex pair shed from this improved wing assembly is less because the vortex cores are (a) expanded, and (b) displaced outboard.

6 Claims, 20 Drawing Figures

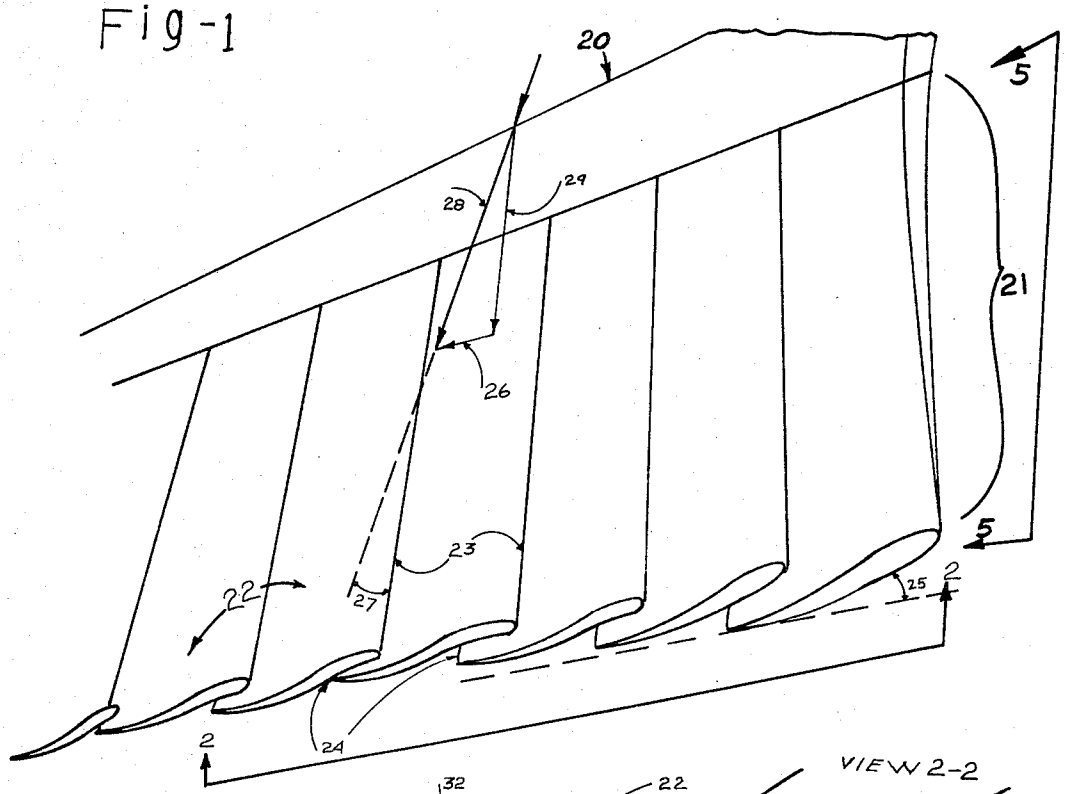


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SHEET 1 OF 7

Fig-1



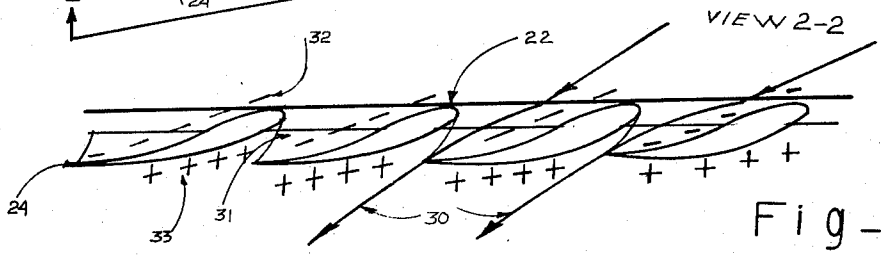


Fig-2

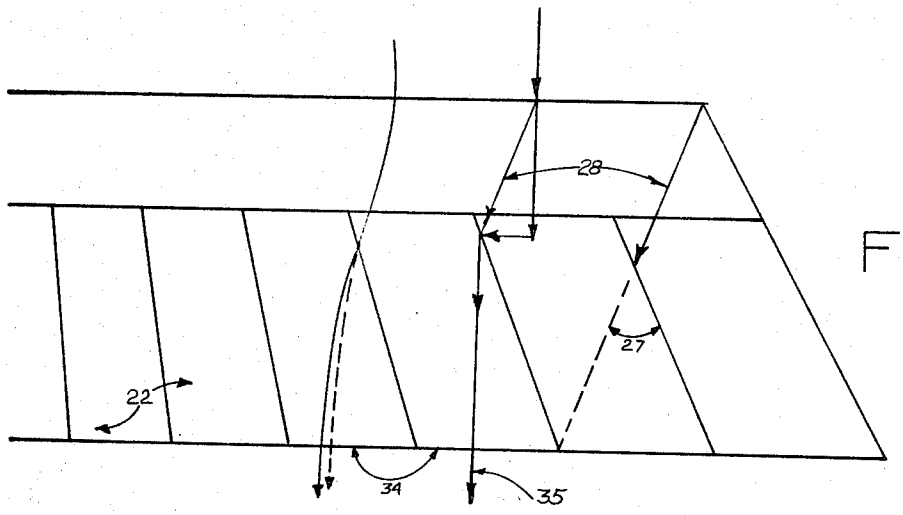


Fig-3

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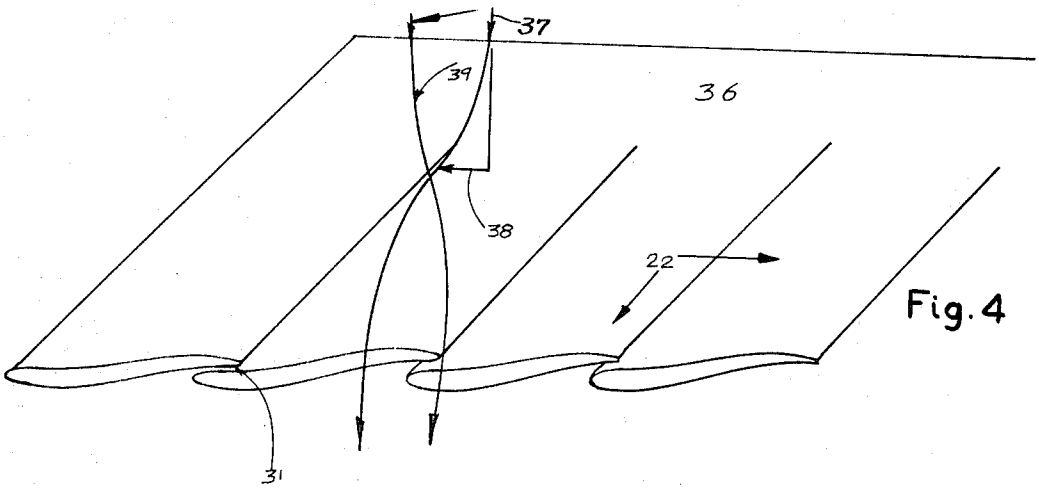


Fig. 4

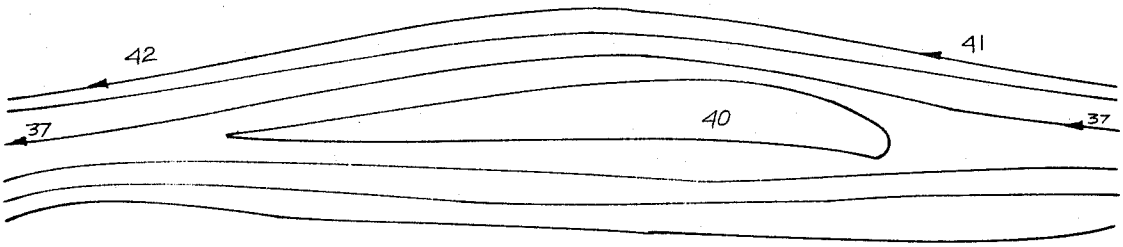


Fig. 5

VIEW 5-5

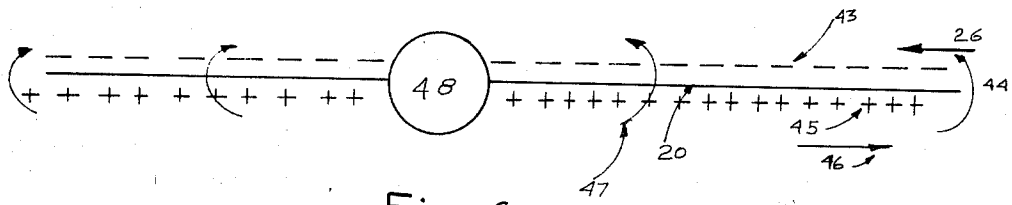


Fig. 6

43<44<45

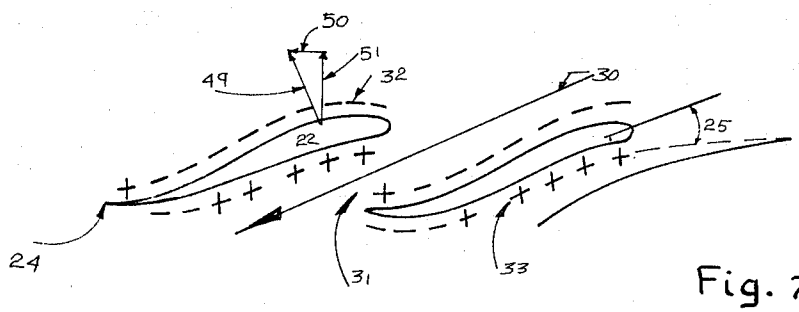


Fig. 7

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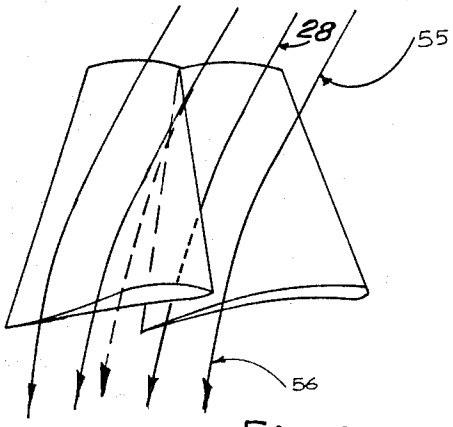


Fig. 9

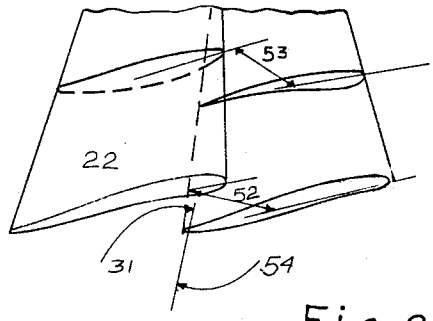
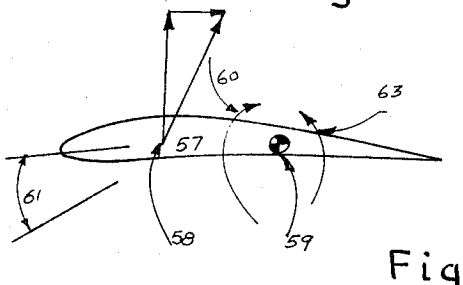


Fig 8



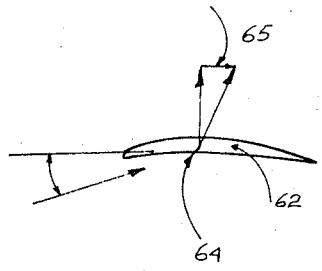


Fig. 10

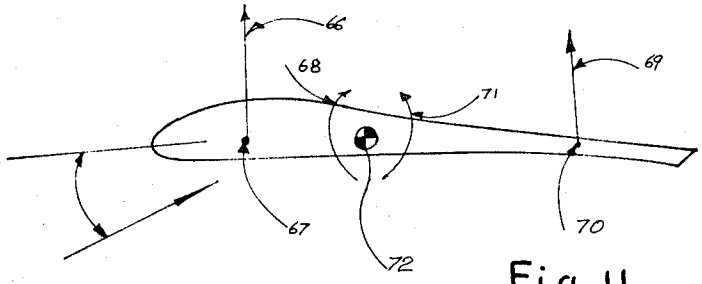


Fig. 11

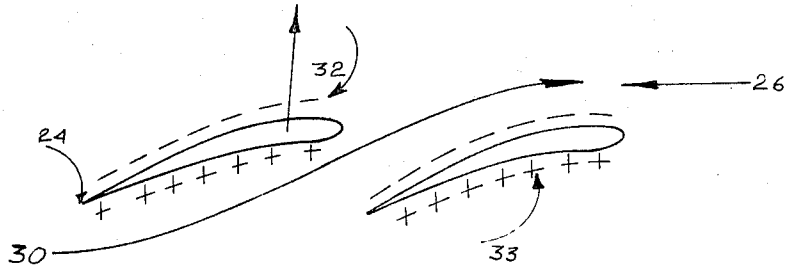
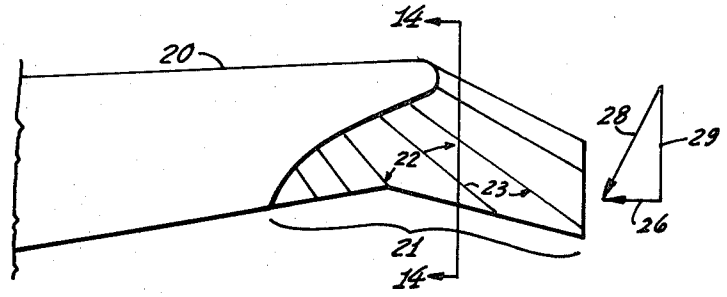


Fig. 12

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Fig. 13



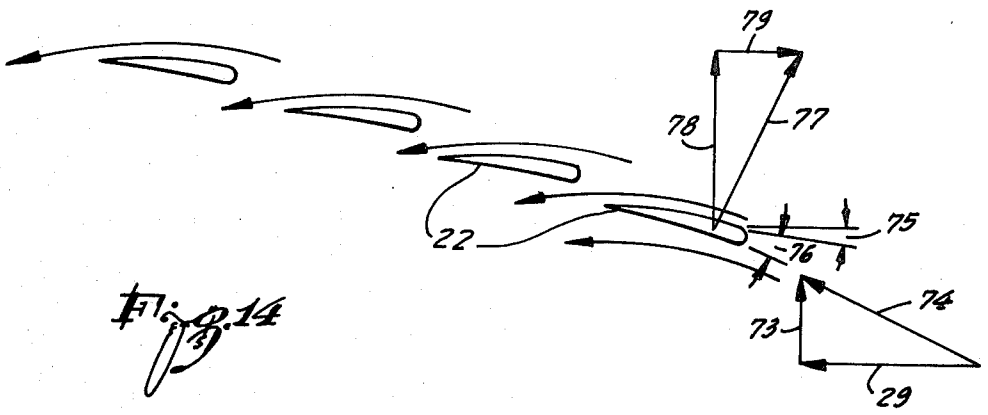


Fig. 14

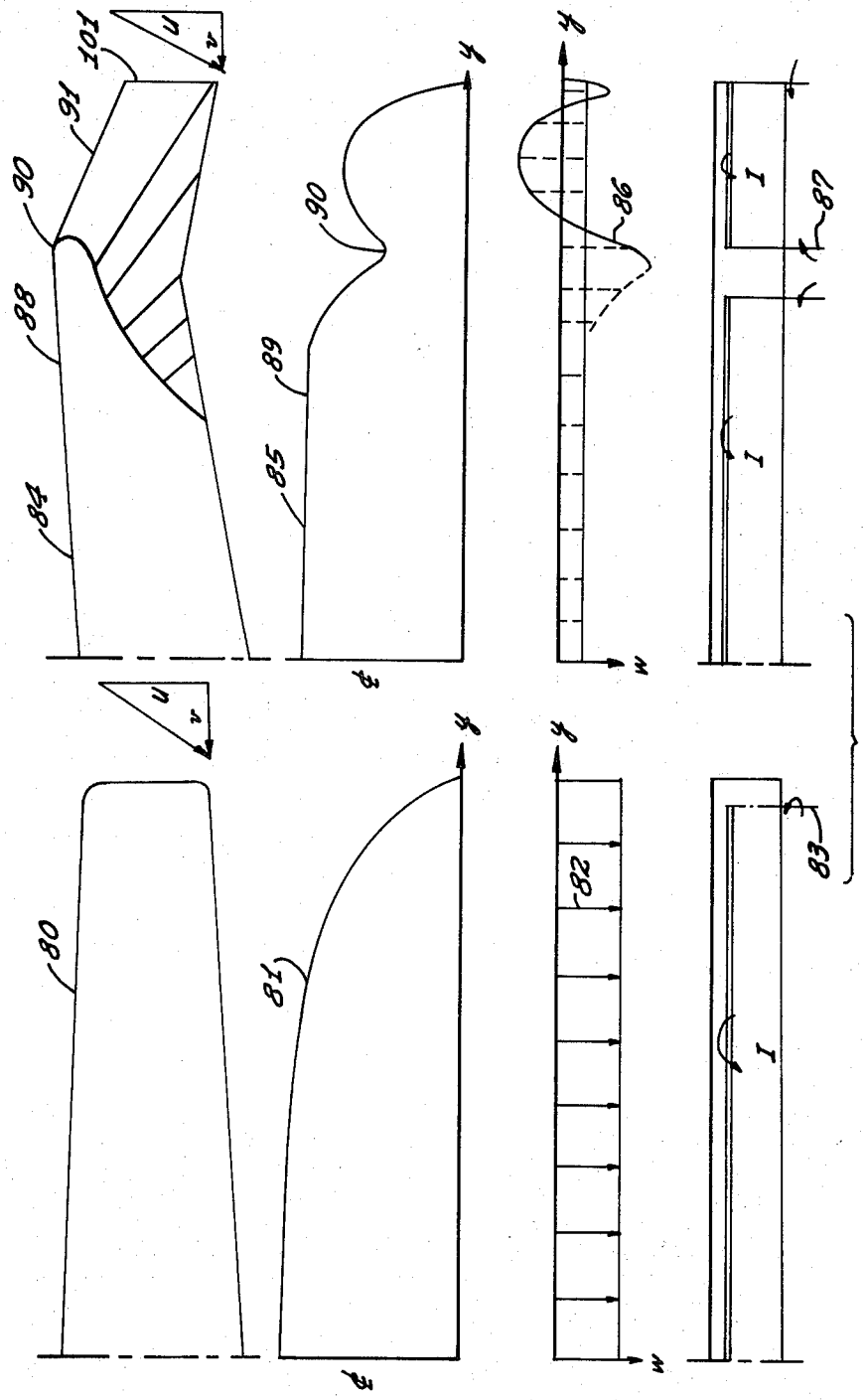


Fig. 15

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Fig. 16

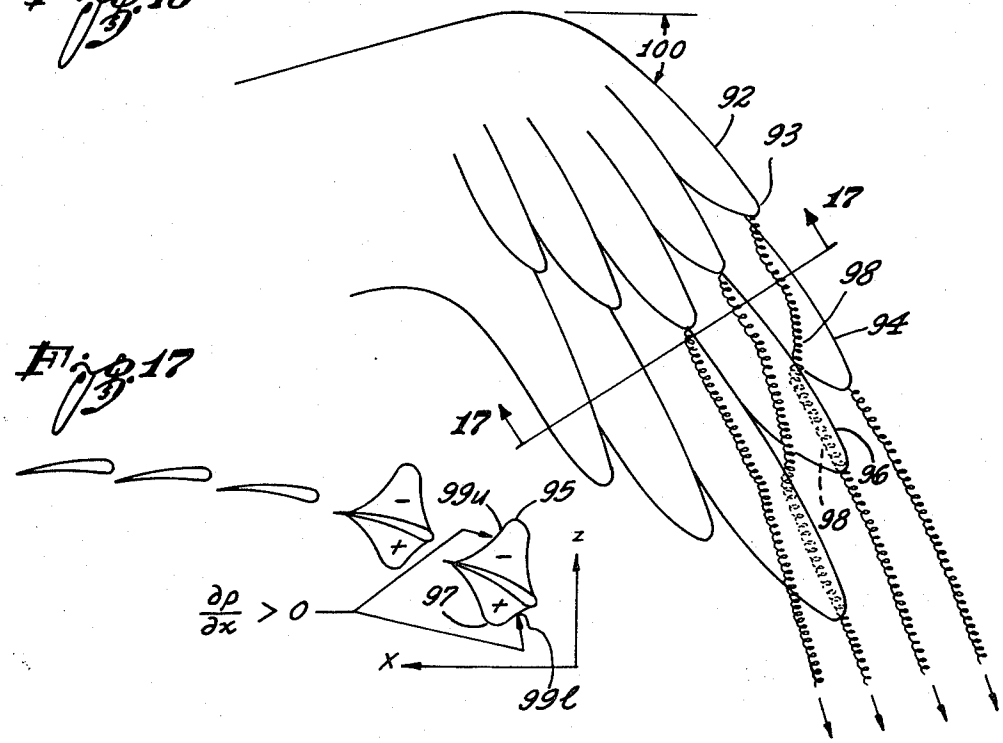
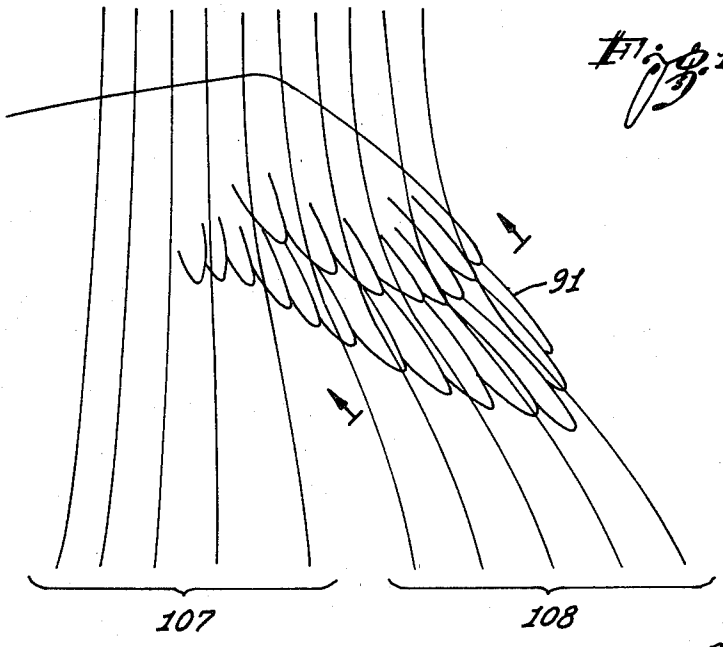


Fig. 17

Fig. 18

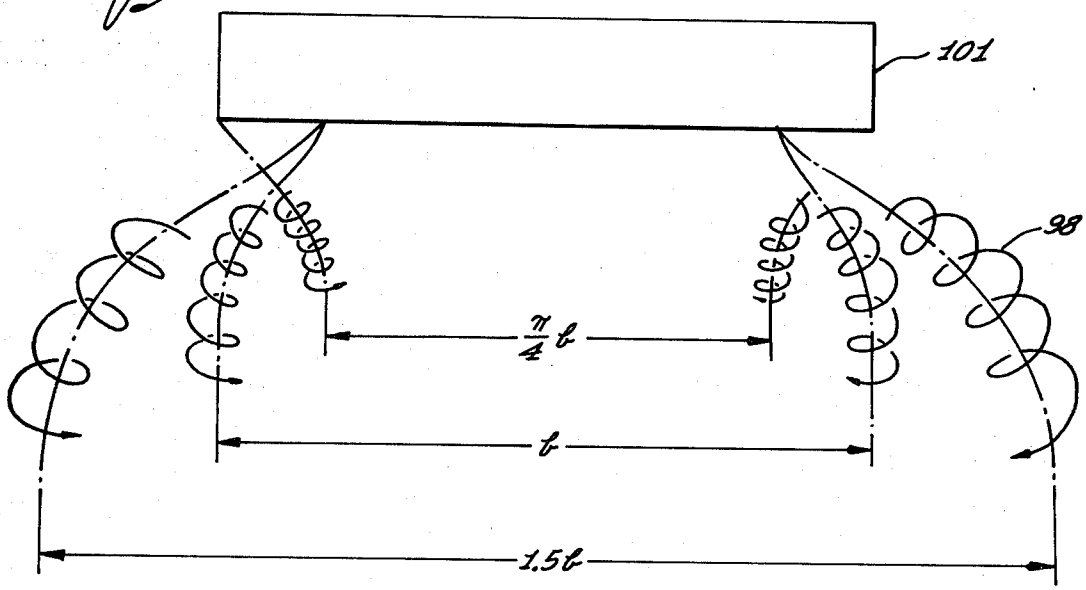


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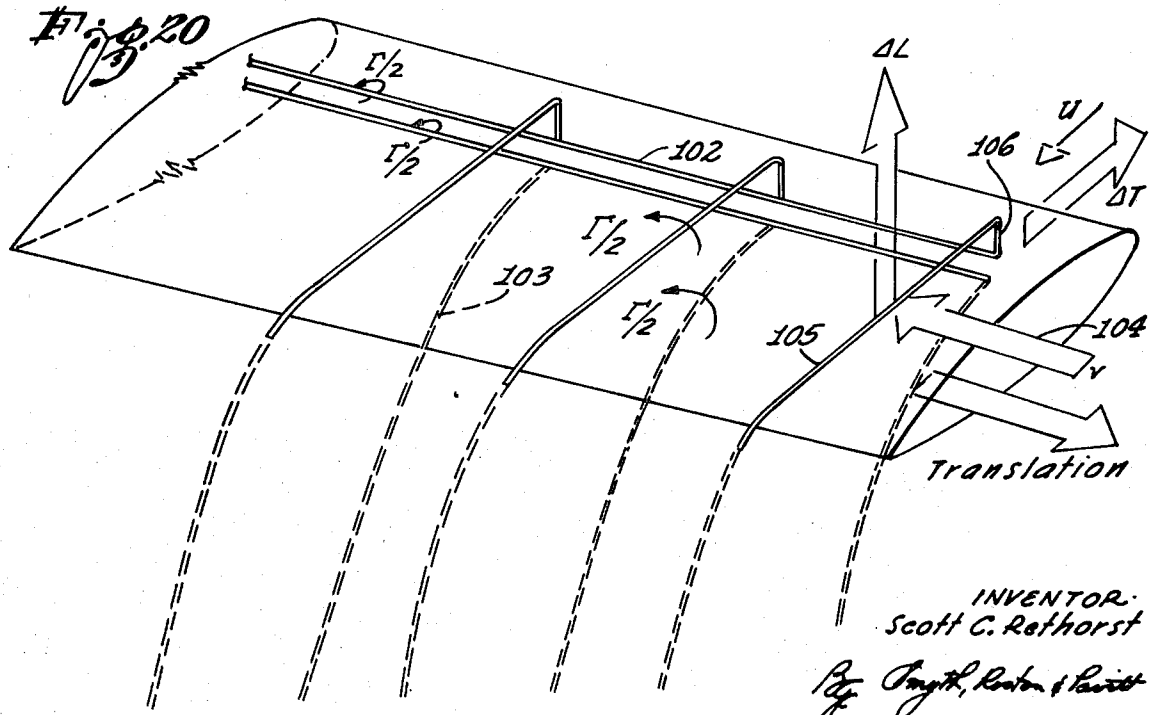
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Fig. 19



Effective Vortex Span	Vortex Location	% Induced Drag Reduction
$\pi/4\ b$	Conventional Wing	0
b	Wing Tip	39
$1.5b$	Outboard of Tip	73

Fig. 20



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SLOTTED DIFFUSER SYSTEM FOR REDUCING AIRCRAFT INDUCED DRAG

This application is a continuation-in-part of application Ser. No. 792,872 filed Jan. 21, 1969, now abandoned.

This application pertains to improvements in the vortex generating and diffusing system disclosed in my U.S. Pat. No. 3,369,775, issued Feb. 20, 1968, and in my continuation application, Ser. No. 706,480, filed Feb. 19, 1968 now U.S. Pat. No. 3,523,661.

My prior U.S. Pat. No. 3,369,775 disclosed a vortex generation and diffusion system comprising a series of vortex diffusers defined by ribs or ridges asymmetric in spanwise cross section on the surface of the wing, and disposed so as to utilize the spanwise flow over a finite span wing to generate and diffuse the normal trailing vorticity within the wing planform into pressure on the backside of the wing.

My continuing application, Ser. No. 706,480, filed Feb. 19, 1968, disclosed an improvement over that of U.S. Pat. No. 3,369,775 consisting of a particular shape and arrangement of the vortex diffusion structure. That is, that the aforementioned ridges are shaped to provide a diffuser concave to the spanwise flow to generate a vortex flow on the underside of the wing providing positive pressure or lift, as well as thrust, and further providing a turned flow on the upper surface of the wing, thereby causing, in one region, reduced pressure and suction lift, and in another region, positive pressure and thrust.

The further improvement of the present invention over that of U.S. Pat. No. 3,369,775 and application Ser. No. 706,840, consists of a particular wing assembly to increase lift and reduce induced drag. This assembly is comprised of (1) a forward conventional primary wing generating lift principally due to the chordwise flow, and (2) an aft secondary wing system having a cascade of swept slotted airfoil-shaped diffuser elements generating lift principally from the spanwise flow and providing a set of air passages leading from the upper to the lower surface of the wing. The terms outboard, inboard, leading edge, trailing edge, forward and aft refer to the primary wing coordinate system even when the secondary wing system is being discussed.

The forward primary wing generates a reduced pressure on its upper surface causing a spanwise inflow, which if unchecked will continue off the trailing edge of the wing assembly, meeting up with a spanwise outflow from the underside, producing trailing vorticity and induces drag. The aft secondary wing system, comprised of slotted and swept-wing elements (trailing edge outboard of leading edge), utilizes the pressure asymmetry on the leading edge of the upper surface of a swept wing to provide an outboard component to the flow. This corrects, to some extent, the inboard component caused by the pressure gradient due to the suction lift on the forward part of the wing. Thus the flow off the trailing edge of this improved wing assembly will be at least partially free from the opposing upper and lower surface spanwise components leading to trailing vorticity and induced drag. It should be noted that the requirement for sweep is relative to the resultant flow, being the vector sum of the chordwise and spanwise flows. Thus, in the presence of a spanwise flow component, the airfoil elements may be oriented directly

aft or parallel to the chordwise flow, thus providing sweep with respect to the resultant flow. Therefore, sweep as used in this document is always to be understood as with reference to the resultant flow.

The swept and slotted airfoil-type diffuser elements are arranged to act as wings with respect to the spanwise flow, thereby developing both suction lift on their upper convex surface and positive pressure lift on their lower concave surface. The air thereafter proceeds inward, downward, and aft through the cascade and diffuses into higher pressure as the air emerges on the lower side of the wing, thereby providing additional lift on the under surface.

On the upper surface of the wing, the gap provided by the swept diffusers faces forward. On the lower surface of the wing, the gap faces aft. Hence, on the upper surface dynamic pressure is imposed on the gap, whereas the pressure on the lower surface is mostly static pressure. To force the air through the diffuser slots from the upper to the lower wing surface, the upper dynamic pressure must exceed the lower static pressure.

The under surfaces of the elements may have straight or reflexed inboard edges to aid in correcting the outboard spanwise component developed by the high pressure on the lower wing surface, thereby further reducing the trailing vorticity.

Thus the spanwise flow, or the spanwise component of the total flow over the upper surface of the wing, performs four functions: (1) the flow passes over the upper convex surface of a small secondary swept wing and in so doing generates lift, (2) the pressure asymmetry due to the sweep of these small secondary wings provides an outward component to the flow, thus correcting the inward component already provided to the air by the primary suction lift over the basic wing, (3) the air continues inward, downward, and aft under the next adjacent inboard diffuser element in the cascade, developing positive pressure lift on the underside of this element due to its concave underside curvature, and (4) in continuing in the direction of the resultant flow the air preferably encounters an expanded slot cross section, thereby further diffusing the velocity energy into pressure as the air emerges on the under and backside of the wing, thus providing further positive pressure lift on the underside and thrust on the backside of the wing elements and cancelling the outboard lower surface spanwise flow component.

The total lift is increased by functions 1, 3, and 4. The induced drag is decreased by functions 2 and 4. The logic is not to put up a barrier or fence to stop the flow, but rather to recognize that the pressure gradient of the primary wing produces both (1) lift, and (2) adverse spanwise flows leading to induced drag. Therefore, the secondary airfoil system is designed to (1) retain the pressure gradient providing the lift, while (2) utilizing the energy of the spanwise flows to correct themselves, thus reducing the induced drag.

The aft secondary wing system also acts as a tail with regard to the forward primary wing, and thereby provides a longitudinally stable lifting assembly. A conventional wing is unstable longitudinally, and requires a lifting surface aft of the center of gravity to provide a stable system, as is well known in aeronautics. In the present wing assembly, the aft secondary swept wing

system performs the function of a tail by providing a lift force located aft of the primary wing and the center of gravity, thereby introducing a moment whose changes with angle of attack make the overall wing assembly stable. This stable wing assembly also eliminates the induced drag produced by lift on the tail.

Furthermore, the slotted structure of the aft secondary wing system prevents flow separation at high angles of attack, i.e., when the aircraft is landing, by enabling the flow to pass in reverse from the bottom surface of the wing up through the slots to the top surface, thereby energizing the boundary layer on the upper side of the wing and preventing flow separation. In a sense, the wing structure at very high angles of attack thus acts as a vented parachute, with the flow through the slots from the bottom high pressure region generating further lift on the airfoil elements in passing through the slotted passages.

Another mechanism for reducing the spanwise flow could be obtained by adjusting the characteristics of the secondary wing system elements so that the flow progresses from the lower to the upper wing surface in all phases of flight. In this case, the high pressure air on the lower wing surface overcomes the spanwise dynamic pressure gradient on the upper wing surface and allows the flow to pass through the wing with the velocity opposing the upper surface inward spanwise flow component. The outward spanwise flow on the lower wing surface provides dynamic pressure to aid in forcing the flow through the slots. Lift is still provided on the convex upper surface of the airfoil elements and the differential spanwise flow between the upper and lower wing surfaces is still eliminated.

The aft, secondary, slotted, and swept wing system also helps maintain the boundary layer laminar on the upper surface of the wing. On a conventional airfoil, it is very difficult for the air flow to negotiate the adverse pressure gradient on the aft portion of the upper surface of the wing, and as a result, the laminar flow generally makes a transition to turbulent flow, with a corresponding higher frictional drag. The aft secondary swept wing system, on the other hand, has a series of short chord wings, providing a low Reynolds number, thereby assisting in maintaining the boundary layer laminar. Furthermore, the cascade-like structure, coupled with the sweep, provides a series of ridges which the spanwise flow must negotiate, and the up and down path over these ridges produces accelerations in the spanwise flow which are large as compared to the accelerations of the chordwise flow, with the result that the boundary layer is dominated by the spanwise flow. This spanwise flow has a very low velocity and hence a low Reynolds number as compared with the chordwise flow, thereby again assisting in maintaining the flow laminar. In addition, the reduced pressure on the upper surface of the airfoil element causes a suction trough extending towards the trailing edge of the wing, providing a favorable pressure gradient route within the adverse primary wing pressure gradient field to assist in maintaining the boundary layer laminar on the aft part of the upper surface of the wing assembly. In the case of the secondary airfoil system elements having reflexed inboard edges, the air flowing into the suction trough diffuses and thereby provides thrust against the concave surfaces of the elements, with the tubular portion of the overlapping *s* curve airfoil elements acting as jet tail pipes, with the spanwise air thus diverted aft providing thrust as a rate of change in momentum acting on the walls of the tubes which provided the deflection of the flow aft.

The airfoil elements of the slotted and swept aft secondary wing system, in conjunction with the spanwise flow, produce a lift force. Because of the angle of attack of these elements, due to their inclination from the upper to the lower surface of the wing, the resultant force normal to the surface is tilted inboard. The vertical component of this force is lift, and the inboard component is analogous to the induced drag component of the resultant force due to the chordwise flow. This inboard component, however, is nearly normal to the direction of motion of the aircraft, and hence represents almost zero work. Hence, this force is primarily an internal stress or compression on the structure, as with other types of diffusers.

The aft secondary wing system as described above is particularly effective on the outboard section of the wing, including the wing tip region itself. The inboard component of the resultant force generated on the airfoil elements, as described above, is the reaction to a change in momentum outboard of the flow past the secondary wing system. Any residual vorticity remaining in this outward deflected flow will then produce an upwash outboard thereof. The secondary wing system in the neighborhood of the wing tip is thus most effectively swept outboard, extended aft, and inclined downward so as to lie parallel to, along side, outboard of, and in close proximity to the residual vorticity, to thereby extract further lift from its upwash.

The lift on the forward primary wing may thus most effectively be reduced inboard of the aft swept tip region, thereby concentrating most of the residual vorticity at the knee or apex where this aft swept tip elements begins.

The airfoil-shaped elements of the aft slotted and swept wing system in acting as airfoils generate an irrotational flow field extending (theoretically) above the surface to infinity. Hence, the outboard flow deflection caused by the pressure asymmetry due to the small swept wing elements is felt in the entire flow field above the wing, not restricted simply to the boundary layer. Other types of flow deflectors (fences, ridges, barriers, end plates, etc.) produce a force only in the plane of the wing and the flow is influenced only over the physical extent of the structure, thereby necessitating large structures to produce appreciable flow changes.

The angle of flow outwards produced by the slotted secondary wing system is greatest at the bottom of the boundary layer, because of the reduction of chordwise velocity near the wing surface, with the angle of flow then decreasing rapidly upwards through the boundary layer. The magnitude of the outward component given to the flow by the pressure asymmetry, however, falls off slowly above the boundary layer, as does the inward component due to the suction lift of the primary wing, so that the rates of decay of these opposing components in the outer flow field are of the same order.

The foregoing and other readily apparent features of my present invention will be better understood by reference to the following more detailed specification and accompanying drawings in which:

FIG. 1 is a perspective view of the preferred embodiment of the aircraft wing assembly, including a forward primary wing and an aft secondary wing system comprised of a cascade of slotted swept diffusers concave to the windward side of the upper surface and extending from the upper to the lower surface of the wing;

FIG. 2 is an enlarged sectional view taken along the line 2—2 of FIG. 1, illustrating the slotted passages from the upper to the lower surfaces of the wing formed by the airfoil-shaped cascade elements;

FIG. 3 is a top plan view of the wing showing sweep, particularly of the outer wing panel, and the resulting outflow of the air over the upper surface;

FIG. 4 is a bottom plan view of the wing showing the outboard spanwise flow component and its cancellation by the inboard component of the upper surface flow passing through the slots;

FIG. 5 is a sectional view along the line 5—5 of FIG. 1, showing the downward deflection of the airflow over the wing;

FIG. 6 is a schematic view, looking forward, of an unslotted wing showing the pressure distribution and resultant spanwise flow on the wing;

FIG. 7 is a schematic rear view of the flow and pressure distribution over an element of the secondary wing system when the elements are arranged such that the flow passes from the upper to the lower wing surface;

FIG. 8 is a perspective view of the slot between two elements increasing in cross section from the forward to the aft ends of the elements;

FIG. 9 is a perspective view of the flow over two airfoil elements;

FIG. 10 is a schematic, looking inboard, of a wing/horizontal tail system used for longitudinal stability on conventional aircraft;

FIG. 11 is a schematic view, looking inboard, of the primary wing/secondary slotted diffuser system, showing the mechanism by which longitudinal stability can be achieved without a horizontal tail;

FIG. 12 is a schematic view of the flow and pressure distribution over an element of the secondary wing system when the elements are arranged such that flow passes from the lower to the upper surface of the wing;

FIG. 13 is a plan view of the outboard region of the wing system, showing the aft swept, outboard, extended wing tip;

FIG. 14 is a vertical section along the line 14-14 through the outboard tip region of FIG. 13;

FIG. 15 is a set of diagrams comparing the features of both a conventional wing and the present improved wing;

FIG. 16 is a plan view of the improved wing system, showing the vortex paths provided by the aft swept, slotted structure;

FIG. 17 is a vertical section view along the line 17—17 through the outer tip region of FIG. 16, showing the pressure profiles on the wing elements;

FIG. 18 is a plan view of the improved wing system, showing a more general view of the outward deflected flow streamlines generated by the aft swept, slotted structure;

FIG. 19 is a schematic view of an aircraft wing, illustrating the vortex patterns provided both by conventional wings and by the outflow of the present improved wing, including a table showing the induced drag reductions thereby provided; and

FIG. 20 is a schematic view of a wing represented by a paired vortex model, the upper set of vortices representing the upper surface of the slotted wing structure and the lower set representing the lower surface of the wing.

In the drawings, like numerals refer to like or corresponding parts throughout the several views. Referring FIG. 1, a wing is illustrated having a forward primary wing 20, and an aft secondary wing system 21 comprising several airfoil-shaped elements 22 arranged in a cascade with their outboard edges 23 pitched higher than their inboard edges 24 to produce positive angles of attack 25 relative to an inboard spanwise flow component 26. The elements are swept at angles 27 relative to the resultant 28 of the chordwise velocity 29 and the spanwise velocity 26.

The flow 30 through the passages 31 between the airflow elements 22 is illustrated in FIG. 2. The low 32 and high 33 pressure regions resulting from this flow are illustrated by minus and plus signs, respectively. The inboard edges 24 may be airfoil-type trailing edges or may be reflexed to form the element cross section into an *s* shape.

The flow turning mechanism by which the inward spanwise velocity component 26 is cancelled is illustrated vectorially by FIG. 3. The elements 22 are swept at angles 27 relative to the resultant velocity vector 28. The sweep produces pressure gradients toward the trailing edges 34 of the elements, thereby providing a resultant velocity vector 35 which is in the chordwise direction of the total wing. This eliminates the vortex producing spanwash on the upper wing surface.

The flow turning mechanism operating on the lower wing surface 36 is illustrated in FIG. 4. The free stream velocity 37 is diverted outboard 38 by the positive lower wing surface pressure gradient. Some of the inward turned flow from the upper surface 39 passes through the slots 31 between the airfoil elements 22 and opposes the outward flow, eliminating the lower surface spanwash.

The mechanism by which the free stream flow 37 is diverted around the wing section 40 is illustrated in FIG. 5. At some distance in front of the wing, an upwash 41 occurs because of the acceleration of the fluid over the cambered upper surface of the wing. The flow directly behind the wing experiences a downwash 42 and then returns to the free stream direction 37 at some distance downstream.

The mechanism by which the spanwise flow over the primary wing 20 is produced is illustrated by FIG. 6. The low pressure area 43 created on top of the wing by the acceleration of the flow, as shown in FIG. 5, is at a lower pressure than the free stream 44, resulting in an inboard spanwise flow 26. The pressure on the lower wing surface 45 is higher than the free stream pressure 44, resulting in an outboard spanwise flow 46. The inboard 26 and outboard 46 components are not necessarily equal, but, if uncorrected on the wing surface, will result in a trailing vorticity 47 with the rotation direction as shown. A schematic fuselage 48 is shown between the two halves of the wing.

The mechanism by which lift is generated in the secondary airfoil system is illustrated schematically in FIG. 7. The flow 30 passing through the slot 31 produces low pressure 32 over the convex upper surface of the airfoil elements 22. In addition to the high

pressure 45 on the lower side of the total wing as shown in FIG. 6, high pressure 33 is generated on the concave underside of the elements. This combination of pressure produces a component of lift 49 on each element. Because of the angle of attack 25 of the elements, the resultant force vector is tilted inboard, allowing its resolution into a lifting component 51 and an inboard component 50. This component 50 is nearly perpendicular to the resultant flow and, therefore, does not create a drag energy loss over the wing. FIG. 7 also illustrates the reflexed inboard edge configuration 24 of the airfoil elements. The flow over the reflexed edges creates an area of lower pressure inboard on the underside of the elements which aids the dynamic pressure gradient in driving the flow from the upper to the lower surface of the wing.

A perspective view of two airfoil elements is illustrated in FIG. 8, showing the slot size increasing toward the trailing edge, i.e., the distance 52 between the tip sections is greater than the distances between more forward sections 53. This increasing slot size acts as a diffuser or jet tube, i.e., the flow expands as it is swept toward the trailing edge, creating a region of higher pressure at the aft end of the slot which acts as a thrust in the chordwise direction 54.

In FIG. 9, a view similar to FIG. 8 shows streamlines 55 of the flow as it is diverted over the secondary wing system. The flow enters the secondary wing system with the resultant velocity 28 imparted by the primary wing. The flow is swept down and aft by the slotted diffuser system and leaves the wing in a chordwise direction 56.

The mechanism by which the primary and secondary wing systems are longitudinally stable as if the assembly were a wing/horizontal tail system on a conventional aircraft is shown in FIG. 10 and 11. A conventional wing 57 usually has a center of lift 58 ahead of the aircraft center of gravity 59 which produces a nose-up moment 60 when the angle of attack 61 is increased. The horizontal tail 62 is added to provide a nose-down moment 63 due to the center of lift of the tail 64 being aft of the center of gravity 59. The horizontal tail has a component of induced drag 65 similar to that of the wing. The primary wing/aft slotted diffuser system of FIG. 11, on the other hand, eliminates the need for a horizintal tail by providing lift both forward and aft of the center of gravity. The lift 66 at the primary wing center of lift 67 produces a nose-up pitching moment 68, while the lift 69 at the secondary wing center of pressure 70 produces a nose-down moment 71 about the center of gravity 72. Since the secondary wing system cancels the primary wing induced drag and has its own angle of attack induced force component directed inboard, both the wing and horizontal tail induced drags are eliminated.

The pressure distribution and resultant lift produced when the angle of attack of the primary wing or the arrangement of the slotted diffusers is such that the flow 30 passes from the lower to the upper surface is illustrated in FIG. 12. Low pressure 32 is generated on the convex upper surface of the elements and high pressure 33 on the concave lower surfaces. The flow, moving outboard, opposes the inward spanwise component 26 of the flow on the upper surface. The inboard edges 24 of the airfoil elements illustrate the straight or nonreflexed element configuration.

The elements of the aft secondary wing system as described above and illustrated in FIG. 1 are further shown in FIG. 13 as they appear in the neighborhood of the wing tip.

A vertical section view taken in the direction of flight through the outboard tip section of FIG. 13 along the line 14—14 illustrates how the vector sum of the upwash 73 generated by the residual inboard vorticity and the free stream velocity 29 provides a resultant upflow 74. The secondary wing elements 22 in this region can then be inclined at a negative angle of incidence 75, thereby providing a force 77 normal to the resultant velocity 74 which has both a lift 78 and a forward thrust component 79. Thus thrust or a reduction in induced drag is obtained from the upwash energy of the residual vortex system.

Conventional planar wings, such as illustrated 80 in the left side of FIG. 15, are designed to minimize induced drag by distributing the downwash resulting from trailing vorticity uniformly across the span. These wings are based on an approximate mathematical model that (a) represents the wing in the x—y plane, and (b) includes no structure to recover the trailing vortex energy into either increased lift or reduced drag. The minimum induced drag for such an approximate model is produced by elliptic lift distribution 81, and has been shown to correspond to a uniform spanwise downwash distribution 82, and a single horseshoe pattern 83, as shown on the left side of FIG. 15 for such a conventional wing.

The right side of FIG. 15 illustrates the improved new wing system of the present invention which is designed to recover the upwash energy, and showing in a corresponding set of diagrams from the top down (a) wing geometry 84, (b) spanwise lift distribution 85, (c) vertical induced velocity distribution 86, and (d) a reverse vortex diagram 87. This improved wing shown in the right side of this figure is designed to maximize lift on its inboard panel 88 with a uniform distribution 89 generating no trailing vorticity, and to dump most of its vorticity at a selected point 90 outboard of the uniform lift but inboard of the wing tip in such a manner as to enable a specifically designed swept and slotted panel 91 outboard thereof to recover a large part of the energy associated with the vorticity dumped from the inboard panel.

The mechanism of energy recovery from upwash is further illustrated in FIGS. 16 and 17. This method employs swept and slotted structure in the outer panel comprising a cascade in the chordwise direction successively providing a short swept element 92 to unload vorticity inboard at its tip 93, a long swept element 94 to transport this vorticity outboard in its upper surface suction trough 95, and a second long element 96 located above and aft to further deflect this vorticity outboard by its lower surface pressure mount 97.

FIG. 16 further shows that the vorticity 98 transported outboard in the upper surface suction trough 95 gradually trails off and under the next aft long element 96 whose lower surface pressure mound 97 in turn deflects the free vortex 98 below further outboard. FIG. 17 illustrates the adverse pressure gradients 99 on both, the upper 99u and lower 99 surfaces of each tip element which in combination with sweep 100 causes the flow to deflect outboard.

Thus, each aft swept element transports vorticity outboard by two mechanisms, a suction trough **95** on its upper surface, and a pressure mound **97** on its lower surface. This improved wing **84** is thus designed specifically for energy recovery and drag reduction, in providing a two element wing, comprising (a) an inboard element **88** having a constant lift distribution **89**, with a sharp drop **90** in its lift distribution and therefore a concentrated dumping of its vorticity at a selected point **90** outboard of the uniform lift but inboard of the wing tip **101**, and (b) a specifically designed panel **91** outboard thereof to recover a large part of the energy associated with the vorticity dumped from the inboard panel **88**.

The paired vortex model illustrated in FIG. **20** represents the improved wing **84** not by the conventional single set of horseshoe vortices **83** in the *x–y* plane, but rather a pair of horseshoe vortices, one above the other. The upper horseshoe vortex set **102** then represents the upper wing surface and slotted structure, including chordwise diffuser structure and outboard swept elements having a chordwise component, as bound vortices. The lower horseshoe system **103** represents the lower wing surface as free trailing vortices, which generate the inboard spanwash **104** over the upper surface of the wing and its diffuser structures or aft swept elements.

An incremental lift ΔL is then generated by this inboard spanwash **104** over the chordwise portion **105** of the upper bound horseshoe vortex system **102**, and a forward thrust ΔT is similarly generated by this inboard spanwash **104** over the vertical legs **106** of the upper bound horseshoe system, where in both cases the incremental force is provided by the Kutta-Joukowsky Law, namely:

$$\Delta F = p v \Gamma$$

where v is the spanwash velocity and Γ is the circulation of the chordwise bound vortex.

Although the vortex strengths shown in FIG. **20** are each $\Gamma/2$, the model is sufficiently general so that (a) the strength of the upper and lower portions may be arbitrarily specified and (b) the upper chordwise portion may be bound and the lower chordwise portion free.

This model thus employs the lower free vortex portion to provide the inward spanwash flow over the circulation strength of the upper bound portion, providing an upward lift force. The upper bound portion, in turn, provides an outward deflection of the lower free vortices. Thus, any residual vorticity shed from both the upper and lower system is deflected outboard, and would lay along side, adjacent to, and parallel to the bound vortices of an aft swept and downward inclined outer wing tip portion such as illustrated in FIG. **16**, thus, maximizing the additional lift from the induced flow, as illustrated in FIG. **20**.

With vortex model, thus, representing the wing by such a horseshoe system, conventional airfoil theory can then be employed to calculate the incremental lift ΔL and incremental thrust ΔT as a function of the wing geometry. Thus, the vortex model is a tool for (a) representing a wing modified in a particular way to recover the spanwash energy with secondary structure such as diffusers or outboard aft swept elements, (b) identifying such modified wings with conventional vortex theory, and (c) enabling the forces and pressures to be calculated by the well developed and test confirmed means of conventional airfoil theory.

The slotted, aft swept, negative dihedral wing **84** illustrated in FIG. **15** and **16** employing the advanced lift distribution and energy recovery mechanism described will locate the vortex core **87** at the knee **90** of the aft swept wing portion **91** and not at the wing tip **101** as in a conventional wing **80**. As a result, the air flow inboard of this vortex will be directed inwards **107**, and outboard of this vortex will be directed outwards **108**, on both sides of the wing.

This flow field, described in detail in FIG. **16**, is further illustrated in a more general manner in FIG. **18**, showing in particular how the slotted and swept structure of the outboard panel **91** produces an outflow **108** which the free vortices **98** must follow. The induced drag reductions corresponding to such outboard vortex displacement are shown in FIG. **19**, which are oversimplified in being based on elliptic lift distribution and no vortex energy recovery, but yet are still illustrative of the gains associated with the effective increase in span provided by deflecting the vorticity outboard.

FIG. **19** also illustrates the well known face (Milne-Thomson, L.M.: "Theoretical Aerodynamics," MacMillan and Company, Ltd., Third Edition, 1958, Section 10.4, page 182 and Section 11.7, page 206) that the dominant inboard spanwash on the upper surface of a conventional wing **80** having elliptic lift distribution **81** reduces the effective span, as determined by the resulting vortex location, to the fraction $\pi/4$ of the span b. The outflow **108** provided by the improved lift distribution and aft swept, slotted structure illustrated in FIG. **18** not only corrects this inboard spanwash, but extends the outflow **108** and its transported vorticity **98** to or beyond the wing span **101** itself, providing the greater effective spans and reduced drags shown in FIG. **19**. Thus, the effective span of conventional wings **80** with elliptic lift distribution **81** is less than the actual wing span, while the present improved wing **84** can develop an effective span greater than that of the structure itself.

The outboard slotted structure **91** in the wing tip region is for the purpose of recovering otherwise dissipated vortex energy and reducing the induced drag. The slotted structure accomplishes this objective in two steps, namely (a) deflecting the vorticity outboard, and (b) locating this vorticity below the lifting elements so that its spanwash and upwash over these elements above produces a force with lift and forward thrust components. The vortex model of FIG. **20** illustrates the inboard spanwash **104** generated from the vortex **103** located below, and shows both the incremental lift ΔL and the incremental thrust ΔT. The corresponding flow model of FIG. **14** shows the thrust **79** generated from the upwash **73**. FIG. **16** shows the vortex outflow sliding below the aft panel elements. It is clear that this mechanism requires the cascade to be stacked above to the rear, so that the free vortices **103** are below the lifting elements **105**. The forward elements may then be oriented with a negative angle of incidence, tilting the resulting force forwards, producing a thrust component **79**, as shown in FIG. **14**.

The term cascade as used in this application refers to a plurality of airfoil-shaped elements located outside of a common airfoil envelope, so that each element of the

cascade operates essentially as an independent airfoil, generating positive pressure on its lower surface and negative pressure on its upper surface, although in sufficient proximity so that each airfoil element operates in the induced flow field of neighboring elements.

These cascade elements as shown in FIG. 14 split the shed vorticity into a corresponding set of vortex sheets, which are shed in a vertical stack, and which then laminate into an expanded size, slowly turning, vortex core. The energy of a pair of vortices such as are shed from a finite span wing is given by [Durand, Wm. Frederick (Editor-in-chief), Aerodynamic Theory, Vol. II, Dover Publications, Inc., New York, 1963]:

$$E=\frac{1}{2\pi}\rho\Gamma^2\left[ln\frac{2b'}{r'}+\frac{1}{4}\right]$$

where

ρ = air density

Γ = circulation strength

b' = semi-span distance between vortex centers

r' = vortex core radius.

In the square brackets the first term is the energy of the outer field and the second term is the energy of the vortex core.

This expression shown that the energy shed into the wake in the vortex system, which is manifest as induced drag, is reduced as the vortex core is (a) expanded, and (b) displaced outboard.

It is clear from this disclosure and its accompanying set of figures that the means of reducing induced drag have been described in detail, and the magnitude of the provisions disclosed may be varied according to engineering considerations for different conditions as required. 22

While the preferred form and method of employing the invention have been described and illustrated, it is to be understood that the invention leads itself to numerous other embodiments without departing from its basic principles.

Having thus described my invention what I claim as novel and desire to secure by Letters of Patent of the United States is:

1. An aircraft wing comprising a primary solid portion and a secondary slotted portion, said secondary portion trailing said primary portion including a cascade of airfoil-shaped elements extending aft and swept outboard of the primary solid portion so as to be parallel to, along side of, outboard of, and in close proximity to any residual vorticity shed from said primary solid portion, and having a negative or lesser angle of attack than the inboard primary solid portion such that when the said primary portion of the wing is operating at a positive amgle of attack, the vector sum of the upwash generated by the residual inboard vorticity and the free stream flight velocity provides a resultant upflow giving a positive angle of attack on the outboard secondary portions, thereby providing a force normal to the resultant velocity which has both a lift and a forward thrust component.

2. An aircraft wing comprising an inboard solid portion and an outboard slotted portion, said outboard portion comprising a plurality of airfoil-shaped elements with the aft ends of said elements swept outboard in a direction beyond said inboard portion, said elements having leading and trailing edges, said leading edges being rounder, thicker, and having a larger radius than said trailing edges which have a thinner, sharper, and lesser radius, said elements having upper and lower surfaces, said upper and lower surfaces being smoothly faired from said leading edges to said trailing edges, said elements being disposed with their centroids stacked vertically above to the rear, said inboard solid portion and said outboard slotted portion being joined in a smoothly faired juncture region, said juncture region having a sharp decrease in angle of attack, or washout, so as to shed the lifting vorticity inboard from the wing tip, the aft sweep of the outboard slotted portion then deflecting the air flow outboard, transporting outward the shed wing tip vortex, said vortex generating an upflow for said outboard slotted wing portion, providing a lift force with a reduced induced drag component.

3. An aircraft as in claim 2 said solid portion having center of lift forward of the aircraft center of gravity, said slotted portion having center of lift aft of the aircraft center of gravity, said aft portion including a cascade of airfoil-shaped elements with the aft ends of said elements swept outboard towards the trailing edge of said wing, the inboard edge of said elements being displaced down and being reflexed in providing passages from the upper to the lower surface of said wing.

4. An aircraft as in Claim 2 said solid portion having center of lift forward of the aircraft center of gravity, said slotted portion having center of lift aft of the aircraft center of gravity.

5. An aircraft wing as in claim 2, said slotted portion including a cascade of airfoil-shaped elements with the aft ends of said elements swept outboard towards the trailing edge of said wing, said elements having chord lengths substantially less than the chord of the wing itself, thereby providing lower Reynolds number and laminar flow.

6. An aircraft wing as in claim 2, said slotted portion including a cascade of airfoil-shaped elements, said elements having chord lengths substantially less than the chord of the wing itself, thereby providing lower Reynolds number and laminar flow.

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