VORTEX GENERATOR FOR AIRPLANE WING

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This invention relates to an airplane wing, fuselage, voluminous chamber or similar body designed for motion through the air. In particular, it relates to such an airplane wing or similar body which is so constructed as to eliminate or accentuate the counterc flow of air along the surface cut by this section has a region which is concave upward. A straight line is considered in this drawing which is tangent to the surface at two points, one upstream of, and one downstream of the concave region. The points of tangency may be either in the groove, or on the adjacent wing surfaces. This is labeled the X-axis. Distance along this axis is labeled x.

The depth of the groove at any point along its length is measured relative to the height of the adjacent ridge in a sectional drawing such as FIG. 11. This depth is measured by drawing a line segment in the sectional drawing perpendicular to the X-axis between a point on the contour of the groove and a point on the contour of the ridge. The length of this segment is denoted d, and the maximum value of d is denoted D.

DIMENSIONAL LIMITS OF INVENTION

(1) A lower limit to the maximum depth of the groove, D, is obtained from the thickness of the boundary layer. D should be at least one half as great as the thickness of the boundary layer existing at the forward end of the corrugations in the operational mode for which the boundary layer is thinnest.

(2) An upper limit to D is obtained from the length (measured parallel to the airflow) of the region downstream of the corrugations in which an adverse pressure gradient exists. D should be no more than one-third of the length of that region in the operational mode in which that region has the greatest length.

(3) The corrugations may be placed in the region of adverse pressure gradient, or may be located upstream of it, provided the aft end of the corrugations is a distance of no more than 20D upstream of the region of adverse pressure gradient in the operational mode in which the region of adverse pressure gradient extends farthest forward.

(4) That portion of the corrugations for which d is greater than 4D should have a length (measured parallel to the corrugations) of no more than 10D (to avoid excessive increases of surface area, which would cause increased drag).

(5) The spanwise distance between the highest points on two ridges separated by a groove of depth D should be no less than D (to avoid excessive increases in the surface area).

(6) The spanwise distance between the deepest point in a groove and the highest point on the adjacent ridge should be no greater than 4D.

(7) It is necessary characteristic of the groove that in a vertical section cut through it following the deepest path from its forward end to its aft end, there is a portion of its contour in the region for which d is greater than 4D which is concave upward. (The term “concave” is meant to include the case of a V-shaped contour.)

(8) It is a necessary characteristic of the ridge that in a vertical section looking in the spanwise direction, three regions may be found on the contour of the ridge; #1 at its leading end, #2 at or near its highest point, and #3 at its trailing end such that the average curvatures in the regions satisfy the inequalities:

\[ K_2 > K_1, \quad K_2 > K_3 \]

(The average curvature in a region is defined to be the angular difference between the tangents to the contour at the ends of the region divided by the length of the contour in the region. Curvature is here defined to be positive if convex upward.)

(9) In the case of grooves and ridges which are symmetrical in any section containing the spanwise and vertical directions, some portion of the corrugations should run parallel to the nominal airflow direction, or at an angle (viewed from above) of no more than 20° from the nominal airflow direction.
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(10) For grooves and ridges which are asymmetrical in some section containing the spanwise and vertical directions, the ridges of the grooves and ridges should be at an angle (viewed from above) of no more than 40° from the nominal airflow direction.

(11) The grooves and ridges should have some steep slopes. In a spanwise-looking section cut along the deepest path through the groove from its leading end to its aft end, a line segment is drawn perpendicular to the X-axis between a point on the contour of the ridge and a point on the contour of the groove. Where this segment meets the contour of the ridge, a tangent to the ridge is drawn. This tangent is at an angle \( \phi \) relative to the X-axis. Likewise, where the segment meets the groove, a tangent to the groove is drawn, which is at an angle \( \phi \) relative to the X-axis. These angles are taken to be positive when they label upward slopes, and negative for downward slopes, relative to the X-axis. The inequality below would then hold:

\[
\int \left| \frac{d}{dx} (\theta - \phi) \right| dx > 60°
\]

The vertical lines denote absolute magnitude, and the integral is taken from a point upstream of the corrugations to a point downstream of them.

**VARIATIONS IN SHAPE**

There are many variations in the shape of the grooves and ridges which are capable of functioning with some degree of efficiency. For example, the highest point on the ridge may be upstream of, adjacent to, or downstream of the deepest point in the groove. The ridge may be either wider or narrower than the groove. In several cases it is desirable for a high, narrow ridge to accompany a wide, shallow groove. The ridge may be so high that it takes the form of a conventional vortex-generating vane. However, it possesses enhanced efficiency because of the accompanying groove.

The grooves and ridges may be either tapered or flared at either or both ends. It is a generally desirable but not necessary feature for the deepest path through the groove from its leading end to its aft end to be parallel to the highest path along the ridge from its leading end to its aft end.

The leading ends of the grooves and ridges may be either gently or steeply inclined. Gentle slopes tend to introduce less drag, whereas steep slopes permit short grooves and ridges; these having the advantage that they retain their efficiency better when the air flows obliquely over the wing (case of sideslip or skid). The grooves and ridges may be curved or straight when viewed from above. If they are curved, it is permissible for them to have a greater inclination to the nominal airflow direction at their aft ends than at their leading ends.

It is generally desirable for the surface to be smooth with no abrupt changes in slope. For example, the ridge should be fairied smoothly into the bottom of the groove without an inside corner. (Such an inside corner would be visible in FIG. 14.) Such an inside corner would cause a slight loss of efficiency. A sharp break in slope at the top of a ridge, however, may be acceptable. In FIG. 14 the top of the ridge would then appear as an outside corner. Abrupt changes of slope which would be visible in FIG. 16 at the leading or aft ends of the grooves or ridges would generally be disadvantageous.

It is usually contemplated that substantially uniform alternating grooves and ridges be employed. This is not a necessity, sometimes, since in some cases nonuniform grooves and ridges can function efficiently.

In some cases vortex generators running parallel to the airflow direction may produce vortices whose sign is reversed relative to the directions shown in FIG. 1. This appears to occur when the boundary layer is relatively thick. Such reversal does not impair operation of the device, provided the vortices are of sufficient strength.

**BRIEF DESCRIPTION OF DRAWINGS**

FIG. 1 is a top view of a portion of an airplane wing attached to a fuselage and showing schematically the vortices formed in the two grooves adjacent a ridge.

FIG. 2 is a transverse section along line 2—2 of FIG. 1.

FIG. 3 is a partial section along line 3—3 of FIG. 1 showing the leading edge.

FIG. 4 is a similar view to FIG. 3 but emphasizing the various angles of the surface.

FIG. 5 is a view taken in a similar manner as FIG. 3 but illustrating a modified NACA 63012 wing section.

FIG. 6 is a similar section to FIG. 5 but taken of a thick wing with a spar.

FIG. 7 is a transverse section of a helicopter rotor modified in accordance with this invention.

FIG. 8 is a partial longitudinal section of a fuselage showing a rear window.

FIG. 9 is a schematic diagram in partial section showing the invention applied to a different shape of voluminous chamber.

FIG. 10 is a schematic diagram with partial section showing another form of voluminous chamber adapted to this invention.

FIG. 11 is a vertical spanwise section of corrugations in a wing cut along the deepest path from its leading end to its aft end.

FIG. 12 is a top view of a portion of an airplane wing on which is mounted a flexible rubber strip containing a plurality of corrugations forming vortex generators.

FIG. 13 is a median portion of a section along line 13—13 of FIG. 11.

FIG. 14 is a median portion of a section along line 14—14 of FIG. 11.

FIG. 15 is a median portion of a section along line 15—15 of FIG. 11.

FIG. 16 is a median portion of a section along line 16—16 of FIG. 11.

FIG. 17 is a section along line 16—16 where the strip is mounted at the extreme leading edge of a wing.

**SPECIFIC EXAMPLES OF INVENTION**

Referring now to FIGS. 1, 2 and 3, the functioning of this invention is illustrated therein. The fuselage 11 is attached to the wing 12 having a leading edge 13. Adjacent the leading edge 13 is a plurality of substantially identical parallel ridges and grooves designated as: ridges 14 through 22 and grooves 114 through 122. The vortex directions are shown in respect to ridge 20 and grooves 120 and 121. Each vortex is indicated by a line and a curved arrow. The line represents the core of the vortex and the curved arrow indicates the direction of rotation of the air in the vortex. As can be seen in FIG. 3, the grooves and ridges are fairly smooth and have gentle slopes at their leading ends and steep slopes at their trailing ends.

Referring now to FIG. 4, angle alpha labels the steepness with which the grooves terminate while angle beta indicates the steepness with which the ridges terminate. Such angles may advantageously be made as great as 30°. Angles much larger than 30° should be avoided as they tend to decrease excessively the downstream velocity of the air, this velocity being the one which must overcome the adverse pressure gradient.

The wing 30 shown in FIG. 5, which is a modification of NACA 63012 wing section, has the corrugations visible at the leading edge. (See NACA report #610, "Tests of Related Forward Camber Airfoils in the Variable Density Wind Tunnel" by F.N. Jacobs, 1937.) The wing has a leading edge 31 with ridge 32 and groove 132 shown in section but otherwise arranged in a parallel array as illustrated in FIGS. 1 and 2. In this wing the counterflow occurring in the upper surface of the wing is reduced so that it can be used for the highest possible lift coefficient. This
wing could be used, for example, in aircraft having short-field landing and takeoff capability, but lacking high-speed cruise capability.

The invention as applied to a wing 40 which has considerable thickness and is symmetrical about a horizontal plane. Such a symmetrical wing permits inverted flight. The thickness is necessary to accommodate a spar 45 usually required to provide sufficient strength with little weight. The wing 40 has a leading edge 41 and a trailing edge 42. Shown in partial cross-section in FIGS. 43 and groove 143 and a lower corrugated zone, as for example, ridge 44 and groove 144. These corrugated zones are placed just ahead of the highly curved regions on the surfaces where the air attains its lowest pressures. The result is that vortices are formed downstream thus suppressing counterflow.

The wing shown in FIG. 7 is actually a helicopter rotor 50 in which 51 designates the forward edge and 52 the rearward edge at a particular instant of time. The rotor, symmetrical front to back, has an upper corrugation area placed symmetrically in the center of the upper surface of the wing and shown illustratively as ridge 53 and groove 153. Whichever way the air flows, vortices are formed downstream of the central regions, where they serve to suppress counterflow. This wing is particularly intended for convertible aircraft having a rotary wing for takeoffs and landings; in which the wing is stopped for cruising flight and held fixed, transverse to the airflow.

FIGS. 8, 9, and 10 illustrate the invention as applied not to a wing, but to the fuselage of an airplane or a similar voluminous chamber intended for motion through the air. Thus in FIG. 8, a portion of an airplane fuselage 60 is shown with the forward end 61 to the left and the tail end 62 to the right. There is a rear window 63 facing aft. This window normally is at a steep angle in order to have good visibility. The result is a highly curved region upstream of the window. Accordingly, corrugations comprising ridges 64 and grooves 164 are provided upstream to reduce the counterflow in accordance with the principles of this invention.

FIG. 9 shows the invention as applied to a voluminous chamber 70 having a constant cross-section over a substantial portion of its length towards the forward end 71. Such a construction is often desirable to maximize the capacity for carrying freight or passengers. The highly curved regions at the aft end 72 are designed to assist in providing rapid convergence of air at the aft end. Upper and lower corrugated sections are therefore provided just forward of this curved section (ridge 73, groove 173, ridge 74, and groove 174) in order to reduce the counterflow formed by this rapid convergence.

The voluminous chamber illustrated in FIG. 10 and designated by the numeral 80 is teardrop in shape with a forward end 81 and a tail 82. There are upper corrugations (ridge 83, grooves 183) and lower corrugations (ridges 84, grooves 184) located approximately at the point of maximum width of the body so as to reduce or eliminate counterflow on the after portion of the body. A voluminous chamber of this design might be used on the fuselage of an airplane.

FIGS. 12 through 17 show the invention embodied in a flexible strip 201 of solid or foam rubber. This strip is meant to be mounted with its major dimension perpendicular to the direction of the airstream, so air flows across it from its leading edge 202 to its trailing edge 203. A sectional view showing several identical vortex generators 204, each consisting of a ridge 205 next to a groove 206. The ridge is close to the groove so the surface of the rubber slopes steeply from the top of the ridge to the bottom of the groove. This steeply sloping surface has the function of pushing laterally on the air in the groove, and thereby introducing vorticity.

FIGURES 13, 14 and 15 show sections cut parallel to the major dimension of the strip; the direction of viewing being parallel to the grooves and ridges. Sections 13 and 15 are cut through the leading and trailing portions (respectively) of the grooves and ridges. Section 14 cuts through the deepest points in the grooves, and the highest points on the ridges. FIGURE 16 is a section cut through the bottom of a groove, facing the steeply sloping surface. This figure shows how the grooves and ridges are cut smooth into the adjacent surfaces upstream and downstream, ridges and grooves, which produce vortices.

FIG. 17 shows a profile section of the leading edge of an airplane wing, with the vortex-generator strip attached to it. De-icing passages 201a are visible in the cross-section of the strip.

OTHER EXAMPLES OF INVENTION

The embodiments described and illustrated above are not intended to limit the scope of this invention. Thus, depending on the construction and design of the wing, the corrugated zone may be located in many other positions. In a wing having two highly curved regions on the underside of the leading edge the corrugated zone would be located between such regions. Such a wing would provide efficient performance at both very high and very low angles of attack. The invention is also applicable to a wing with a slotted flap. In this case the corrugations can be placed at the leading edge of the flap where they help the air change direction to flow down over the flap. In addition, the invention can be applied to a bi-plane by applying corrugations on the bracing members and wings just upstream of the regions where counterflow tends to occur. Also, corrugations can be provided where the wings are attached to the fuselage, since adverse pressure gradients produced by the wings tend to cause counterflow on the fuselage. In general it is desirable that the surface of the wing or other body and the corrugations on it be smooth and devoid of protruding rivets and the like. Relatively short grooves and ridges are usually employed.

I claim:

1. An airplane wing, fuselage, voluminous chamber, or similar body having surface corrugations in or near a region where counterflow is expected; said corrugations comprising alternating ridges and grooves shaped so as to deflect the air flowing along the surface of the body to produce vortices which trail downstream and serve to bring fast moving air into the boundary layer; said corrugations being spread either in the region of adverse pressure gradient of upstream thereof no further than twenty times the maximum depth of the groove relative to the adjacent ridge; said grooves and ridges having some steep slopes; the grooves and ridges being so shaped that a moving air going along the surface of the body in a direction perpendicular to the airstream reveals a portion of the groove contour having depth exceeding one half the maximum depth and curvature which is concave toward the airstream; a portion of the ridge contour in said view being convex toward the airstream with regions of less curvature upstream and downstream; that portion of the corrugations for which
the depth of the groove exceeds three fourths of the maximum depth having a length no greater than ten times the maximum depth of the groove.

2. Claim 1 wherein the corrugations are contained in a flexible strip attached to the body.

3. Claim 2 wherein said strips contain passageways for ice removal liquids.

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