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The use of vortex generators to improve the take-off and landing characteristics of transport category aircraft

V.G. Tsipenko[1], M.V. Sagaydak[2], V.I. Shevyakov[2]
[1]Moscow State Technical University of Civil Aviation, Moscow, Russia
[2]IRKUT Corporation Regional Aircraft Branch, Moscow, Russia

Abstract: The issue of using vortex generators to improve the take-off and landing characteristics of a transport category aircraft has been considered. Three directions have been analyzed. The first: the installation of vortex generators on the nacelles of the main engines to increase the maximum value of the lift coefficient in landing modes. The second: the installation of vortex generators on the upper surface of the flap to increase the lifting characteristics of the wing by improving the flow around the flap. The third: the installation of vortex generators in the tail unit to increase the efficiency of control surfaces and reducing handling speeds. Examples of the use of vortex generators in each of the directions are given. It is shown that the improvement of the aerodynamic characteristics of the aircraft is possible in the presence of wing separation boundaries on the lifting surfaces in flight operating modes and the elimination of these zones by installing vortex generators. The results of computational studies, experiments in wind tunnels, as well as data from flight tests of an experimental aircraft confirming the effectiveness of using vortex generators are presented. The concept of increasing their stability by installing vortex generators in places with maximum flow velocity is proposed. Considering this concept, new locations for installing vortex generators on the upper surface of the flap, as well as on the fin of an experimental aircraft for repeated flight tests have been selected. The installation of vortex generators on the fin involves increasing the efficiency of the rudder to reduce the handling speeds. The possibilities of optimizing the parameters of the installation of vortex generators are considered. Recommendations are given on the choice of shape, size, and angles of their installation, depending on the tasks solved with the help of vortex generators and considering the possible increase in drag from their installation.

Key words: aircraft, local aerodynamics, local flow separation, vortex generator, vortex harness, bearing surfaces, controls, harmful resistance, installation parameters.

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Использование вихрегенераторов для улучшения взлетно-посадочных характеристик самолетов транспортной категории

В.Г. Ципенко[1], М.В. Сагайдак[2], В.И. Шевяков[2]
[1]Московский государственный технический университет гражданской авиации, г. Москва, Россия
[2] ПАО «Корпорация "Иркут"» филиал «Региональные самолеты», г. Москва, Россия

Аннотация: Рассмотрен вопрос использования вихрегенераторов для улучшения взлетно-посадочных характеристик самолета транспортной категории. Проанализированы три направления. Первое – установка вихрегенераторов на мотогондолах маршевых двигателей для повышения максимального значения коэффициента подъемной силы на посадочных режимах. Второе – установка вихрегенераторов на верхней поверхности закрылка для повышения несущих свойств крыла за счет улучшения обтекания закрылка. Третье – установка вихрегенераторов на хвостовом оперении для повышения эффективности органов управления и снижения эволютивных скоростей. Приведены примеры использования вихрегенераторов по каждому из направлений. Показано, что улучшение аэродинамических характеристик самолета возможно при наличии отрывных зон на несущих поверхностях на рабочих режимах полета и ликвидации этих зон путем установки вихрегенераторов. Представлены результаты расчетных исследований, экспериментов в аэродинамических трубах, а также данные летных испытаний опытного самолета, подтверждающие эффективность использования вихрегенераторов. Проанализирована физика образования вихревых жгутов. Предложена концепция повышения их устойчивости путем установки вихрегенераторов в местах с максимальной скоростью потока. С учетом этой концепции выбраны новые места установки вихрегенераторов на верхней поверхности закрылка, а также на киле опытного самолета для проведения повторных летных испытаний. Установка вихрегенераторов на киле предполагает повышение эффективности руля направления для снижения эволютивных скоростей. Рассмотрены возможности оптимизации параметров установки вихрегенераторов. Приведены рекомендации по выбору формы, размерам, углам их установки в зависимости от решаемых при помощи вихрегенераторов задач и с учетом возможного увеличения лобового сопротивления от их установки.

Ключевые слова: самолет, местная аэродинамика, локальный отрыв потока, вихрегенератор, вихревой жгут, несущие поверхности, органы управления, вредное сопротивление, параметры установки.

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Introduction

At a certain point the flow separation sections appear on a wing upper surface while increasing the aircraft angle of attack. This leads to the decrease of wing lifting characteristics and the aircraft flight characteristics deterioration. There are similar phenomena on the upper surfaces of high lift devices and flight controls at high deflection angles – the flow separation decreases their efficiency. Using the stable vortex harnesses for flow stabilization is one of the ways to “postpone” the emergence of separation phenomena on the aircraft upper surface. Such harnesses may be made using special devices – vortex generators (VG). The simple VG constructions in the form of flat plates set on the upper surface at some angle towards the ram (incoming) flow are those used in aviation more frequently. They may be set on the upper surfaces of the wing, flap, on the engine nacelles, on the tail. The VGs in the form of rectangle, triangle or trapezoid are the most widespread ones, sometimes the VGs are paired up (fig. 1). Their geometry is diverse, but the work principle is the same – making the longitudinal vortices.

The use of VG, as a passive flow management technology element, was initially proposed in 1947 [1] by Tailor. Since then, there has been a lot of calculation and experimental studies (for example, [2–6]), dedicated to research of vortices, made by VGs, nevertheless, the general theory of the phenomenon is not elaborated profoundly enough and the clear recommendations on VG parameters recognition and their setting to get the required effect have not been developed so far.

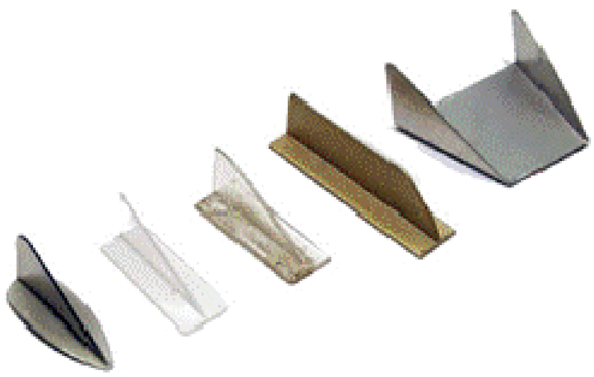

Fig. 1. Various types of vortex generators

The practical questions of VG use with an aim to enhance the aircraft field performance are discussed in the following work.

VG use experience in aviation

VG use in aviation can be relatively divided into several areas: setting of the VGs on the engine nacelles, on the upper surfaces of the wing, on HLDs, in the tail unit.

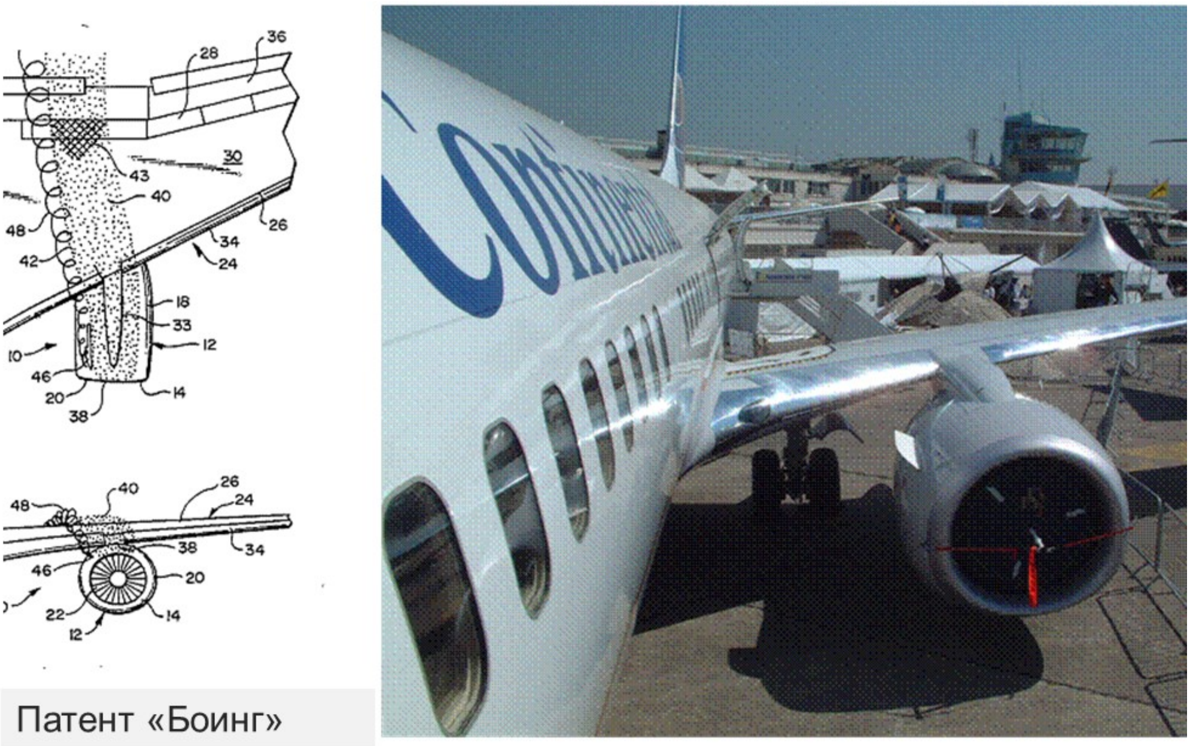

Fig. 2. Vortex generator on the engine nacelle

The use of VGs on the main engine nacelles is one of the most known and widespread way of their implementation. The idea of using the vortex harness sustainability as the separation limiter on the wing upper surface due to negative impact of the engine nacelle while increasing the aircraft angle of attack is shown, for instance, in Boeing *US Patent № 4540143, 1985.* The VGs are usually set on the inner engine nacelles (fig. 2) for these purposes. Sometimes they also use the extra VGs, which are set on the outer side of engine nacelle.

Such VGs allow us to decrease lift losses. On some planes the separation area is due to the flow from the gap between the pylon and the deflected slat (fig. 3). The number of the VGs being set on the engine nacelles depends on physics of the process and the direction of flow separation area, nevertheless, in this case the main purpose of VG use remains unchanged – the increase of the aircraft max lifting capacity.

Nevertheless, it should be mentioned, that the effect from setting the one VG, as well as the two, occurs only whether the vortices hit the upper wing surface.

It is necessary to increase the wing lifting characteristics and/or to enhance the aerodynamic features while take-off to improve the field performance. VGs will help us do that only whether there are the separation areas on the wings in operational modes. Closing of the separation area will allow us to improve the wing flow and increase the lifting capacity. It is a challenge to decrease the flow resistance while using the VGs.

There are a lot of papers, for example, [7–9], on the topic of high lift devices efficiency increase. There are some cases of researching the diverse VG setting on power airfoil. Setting of converging VG on the lower surface of the inner wing in front of the deflected flap (fig. 4, on the left) is surveyed in the work [10]. The interesting place for VG setting is suggested in paper [11], where

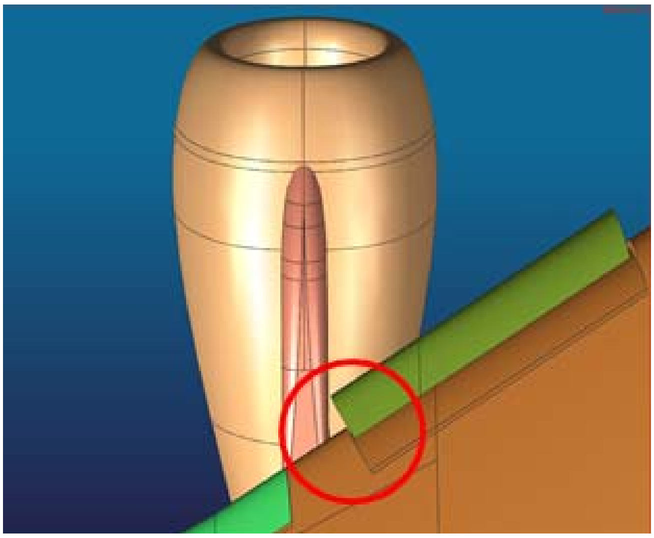

Fig. 3. The gap between the pylon and the slat

Fig. 4. Various options for installing vortex generators

the VGs are set on the surface of the inner wing in the gap between the wing and the flap (fig. 4, on the right).

The negative aspects should be mentioned, without estimating the effect of VG use in these cases: additional drag due to VG constantly being in the flow at an angle to it in the first case, and the impossibility of flap proper fairing to the wing core due to the flap and VG interference, in the second one. Both variants are not appropriate for the high-velocity aircraft, as they lead to aircraft performance deterioration.

Nowadays VGs are installed on the flap upper surface on some aircraft. Boeing 777 (fig. 5) may serve as an example.

In general, VG setting to "postpone" the separation on the flap is a rather efficient way of increasing the aircraft lift performance while take-off and landing in case there is a flow separation in this area. That is why the issue of VG setting should be resolved strictly for the certain aircraft type.

Increasing of the wing lift performance leads to the decrease of landing and take-off speeds, however, there are also limits at this very point – in terms of handling velocities, related to the controls efficiency. The demand for the high controls efficiency at low velocities forces us to use maximum angle of attacks of the controls surfaces, which leads to the separations occurring on them. The possible ways

Fig. 5. Installation of vortex generators on the flap

of "postponing" the separation phenomena on the controls – is using of stable vortex structures or single-slotted controls.

The use of VGs for purpose of controls efficiency increasing – is not the new approach, already implemented in practical aviation. VGs are set on both horizontal and vertical tail units of small aircraft, ones, to facilitate the elevators and rudder respectively (www.blackmaxbraks.com).

It should be mentioned, that the lower surface of the horizontal part of the tail unit is the crucial area due to negative lift generation, that is why VGs are set exactly on it.

The physics of the process. VG efficiency

It is necessary to understand the physics of the phenomenon, in order to apply VG properly. According to the widespread theory of preventing the friction boundary layer from separation with the VG, going beyond the friction boundary layer edge, the effect occurs due to the energy shift into the friction boundary layer from the outer flow and velocity profile change in it [12] (fig. 6).

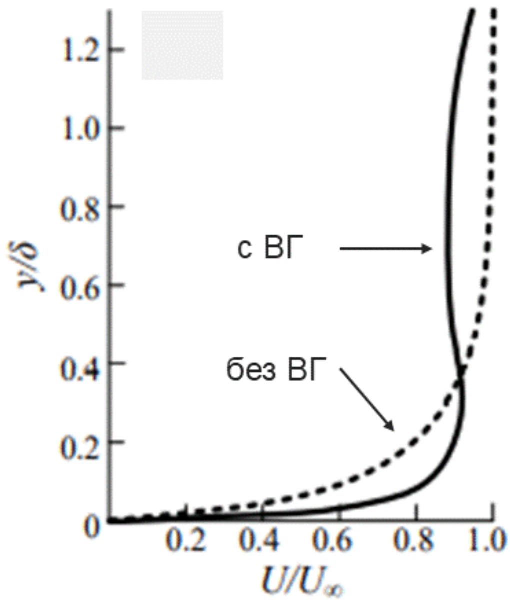

Fig. 6. Effect of the vortex generator on the velocity profile in the boundary layer

However, another approach is also possible. It can be said that the intensity and stability of the resulting vortex from the VG is the most important aspect in terms of influencing the outer flow. It is not that crucial whether the friction boundary layer gets extra energy in purpose of gaining the effect, nevertheless, it is important to “postpone” the separation of the friction boundary layer. The effect of “postponing” the friction boundary layer separation can be presented schematically as a result of its “covering” upwards with the vortex harnesses from the VG. According to this, the system of stable vortices above the friction boundary layer should be organized in purpose of “postponing” its separation.

In fact, VG – is a mini wing and by analogy with a big one it can be said, that its tip vortex will dismount while generating the “lifting” force – transverse one in this very case. VG should have a “gliding angle” to the approach flow in this purpose. The direction of vortex spinning is set depending on the VG set angle and the force act direction.

VG may become an ordinary extra harmful resistance source and even provoke the local flow separation without the effect of transverse force generation. Perhaps, that is why they failed to get the effect of extra lifting force generation while aircraft model test activity in wind channel [13] – the VG sizes turned out to be so small while scaling up, that they were not forming the stable vortex, but became the small local flow separation sources, changing the flow direction on the flap without the effect. This effect may be got whether the VG geometry is modelled properly and the model scale is large enough. For example, the effect of VG use on the flap is shown while testing a half-model of the A340 aircraft in wind channel (fig. 7).

It is shown that the separation area, almost on the two thirds of the flap surface, has almost disappeared after VG setting (fig. 8). And, consequently, the half-model aerodynamic features have improved, and the stalling angle has expanded significantly [9].

Efficiency of VG use depends on their setting parameters. The VG form and height, their being set chordwise, the angle of setting towards the flow, distance between the VGs refer to such parameters.

The main VG aim – is making a stable vortex in a right place. It is necessary to provide circumstances, which this vortex will be made in. There is a sufficient number of pa-

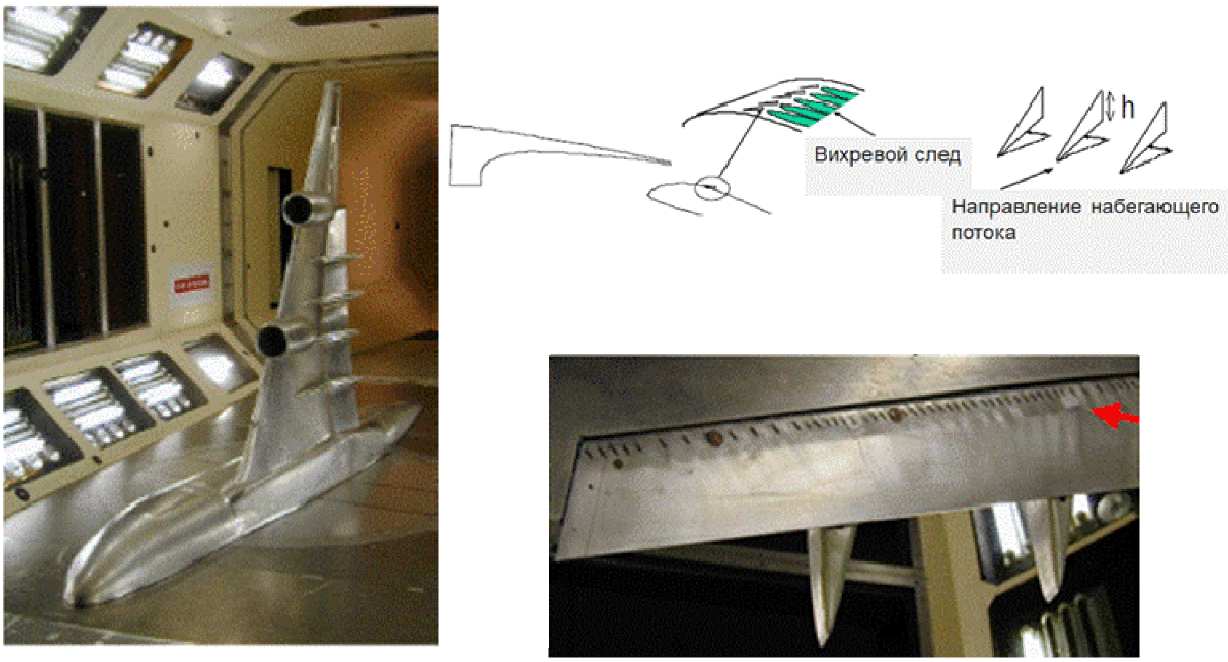

Fig. 7. A half-model of the A340 aircraft with vortex generators on the flap

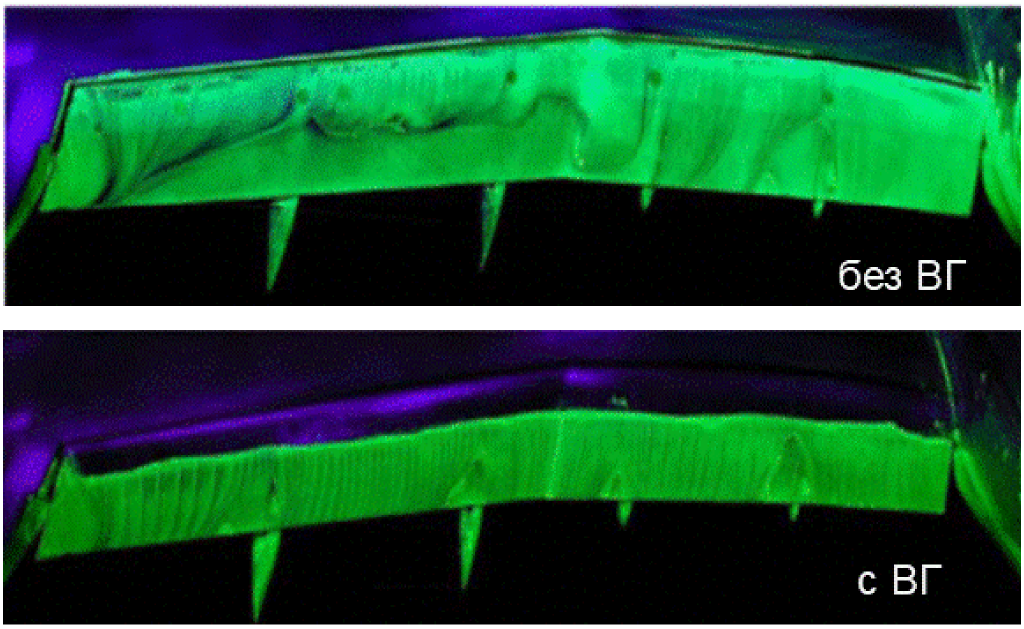

Fig. 8. Visualization of the flow around the flap of the A-340 half-model aircraft

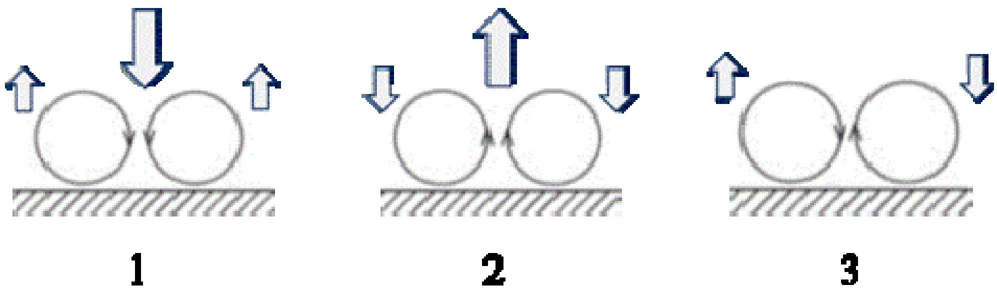

Fig. 9. Vortex rotation schemes

pers on the topic of vortex making process, both computational and experimental ones. Nevertheless, the general enough theory of the phenomenon is not elaborated profoundly enough and the clear recommendations on VG parameters recognition and their setting in order to get the demanded effect have not been developed so far.

The big number of works is dedicated to the search of the optimal VG location on the aircraft and the VG setting relating to the flow in purpose of getting the maximum effect and VG use analysis depending on their types. Setting the VGs parallel to each other is the simplest way. The diffuser VGs [14, 15] are also used. Vortices of various direction (fig. 9) will be used depending on VG setting. The directions and intensity of the local speeds stimulated by vortices are shown with arrows. There the diffusor VG vortices on scheme 1, converging – on scheme 2, vortices of the two VGs, set at the same angle towards the flow – on scheme 3.

The data on one or another VG type efficiency is diverse. For example, in work [16] it is shown, that the efficiency of simple VGs, parallel to each other, and of diffusor ones is the same for rectangular wings, and of the converging ones – is significantly less. In work [17] it is described, that the diffusor VGs are two times more efficient, than the simple ones, parallel to each other. The theoretical justification of such a conclusion – is that the various vortex spinning direction allows us to make a more stable vortex system, which provides the VG use efficiency. The question is controversial and should be scrupulously researched. However the conclusion of the schemes in Figure 9 is that the intensive component of speed, directed upwards, does not contribute to frictional boundary layer stability in VG setting area.

Vortex intensity depends on VG side force, as well as vortex intensity behind the wing depends on its lift. This power is in proportion to the VG flow squared velocity. According to this suggestion, VG height should, firstly, be more, than its depth, as the speed rate inside VG is small; secondly, it is desirable to find an area for VG setting with the highest flow speed rates and outside the frictional boundary layer. The area for VG setting can be established with the calculation methods according to the demands of the maximum speed close to the surface. It is possible to implement the approximate methods in purpose of frictional boundary layer depth detection.

The angle of VG setting should be enough for generating a side force, which stimulates spinning, and making a stable vortex due to VG and flow interference. The angle of setting should not, certainly, be large due to the extra harmful resistance occurrence, nevertheless, it cannot be small either, as there will not be a stable vortex. The value of 15÷17° is frequently enough in relation to the local flow direction in VG setting area.

The issue of the optimal distance between the VGs is equally important – as the effect of VG use may be low in case of their infrequent setting, and it may disappear in case of a too frequent one due to vortex interference with each other and the loss of their stability. It should be considered that the number of VGs, as well as the harmful resistance, depends on distance between them. The distance is usually from 1 to 3% for wing devices and from 5 to 10% for the maximum tail chord (www.blackmaxbraks.com) in low-speed aircraft. The VGs are usually set at the equal distance from one another.

The peculiarities of practical VG use in aircraft

In practice the issue of improving the aircraft take-off and landing characteristics is divided into two directions: increasing the wing lifting and controls efficiency.

For example, in work [13] they have found out the presence of separation area on the flap upper surface in aircraft landing configuration in operational mode. That has allowed us to look forward to the opportunity of separation elimination with the help of VGs and for increase of wing lifting characteristics, respectively. It is noted in work [13], that the previous calculation studies showed us the presence of separation phenomena on the flap. Then the data of the aircraft flight testing while visualizing the flap flow by “tufting technique” have confirmed that. The opportunity of VG use on the upper flap surface is also considered in purpose of “postponing” the separation phenomena.

The forms of VG – triangle and trapezoid one – are researched with calculation methods. VGs were set ratably by the flap span, at the same angle to symmetry axis with the nose outside. Their height has been limited by the gap value to the wing structure elements. VG setting by the flap chord was established by the maximum flow acceleration area (minimum pressure coefficient value Cp) on upper surface in the respectful flap section, which should provide vortex intensity and stability (fig. 10).

As a result of calculation studies there was no VG influence on lifting power maximum coefficient while various Reynolds numbers stated, although the pattern of flap flow while VG setting was changing. Experimental studies on the aircraft aerodynamic model in wind channel have not stated VG influence on total aerodynamic characteristics, which can be explained by the difficulty of VG modelling

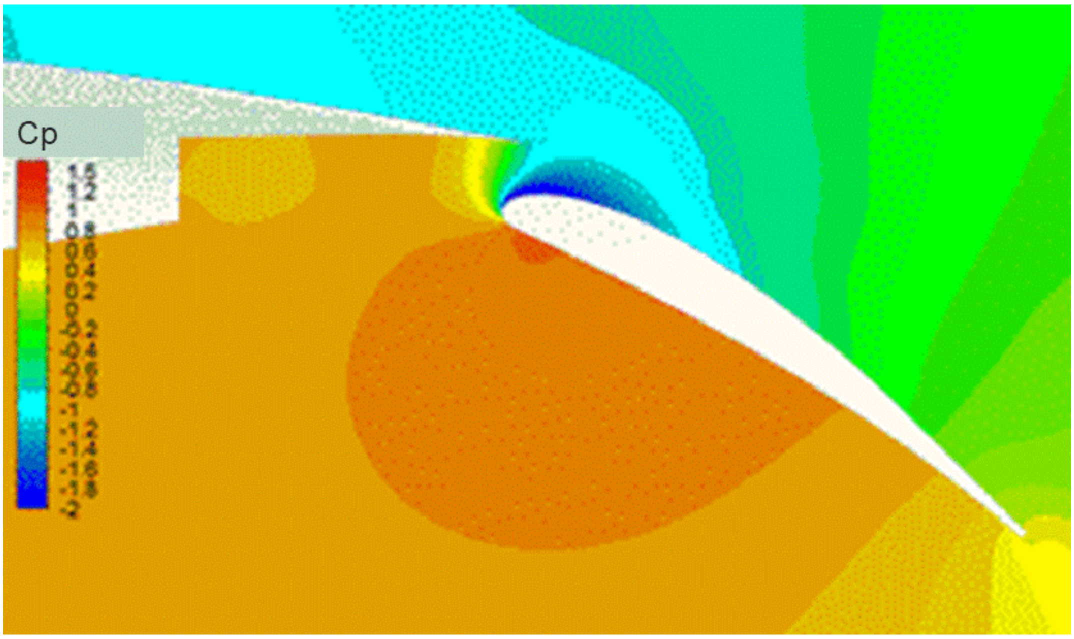

Fig. 10. Calculated distribution of the pressure coefficient in the flap area

while the scale of the model is relatively small (VG height was 1.0÷1.4 mm). The character of the flap upper surface flow has a little bit changed.

The aircraft flight testing was conducted for the analysis of VG setting influence on aerodynamic characteristics. The trapezoid VGs were set on the flap upper surface with pitch of 200 mm along the flap slap at the angle of 15° to the aircraft centerline with the nose outside.

Flights on the large angle of attack showed us, that there is an effect of VG setting. Particularly, proceeding of flight-testing results with the use of regressive analysis methods allowed us to state the influence of VG on the maximum lifting power coefficient value for the landing configuration. That allows us to enhance the aircraft take-off and landing characteristics and expand its expected operation circumstances. Possible extra decrease in take-off and landing speeds may demand a decrease in handling speed.

To facilitate this, VGs are set on in the tail unit. The development of the stable vortices with the help of VGs allows us to look forward to increase in flight control surface efficiency. Particularly, there are plans to run the aircraft flight testing with the aim of studying the possible increase in flight control surface efficiency. The optimal variant – is to set VGs on the forward part of the flight control surface, and appearance of VGs in the flow was only in case of large deviation angles of the flight control surface. VGs are inside the fin in cruising modes and do not develop additional harmful drag in this very case. Nevertheless, it is not always possible due to the small distance between the fin and elevator surfaces. VG height may not be enough for making a stable vortex in this case. VG setting on the fin in front of the flight control surface is less beneficial from the point of view of local speeds, nevertheless, it is, certainly, easier to be implemented. Besides that, such a setting will lead to the undesirable increase in drag in cruising mode, as it is necessary to set VGs at some angle to the flow in purpose of making a stable downward vortex. Although, according to the aircraft flow calculation, flow lines on the fin in cruising mode have some gradient (fig. 11), which decreases the local VG angle of attack.

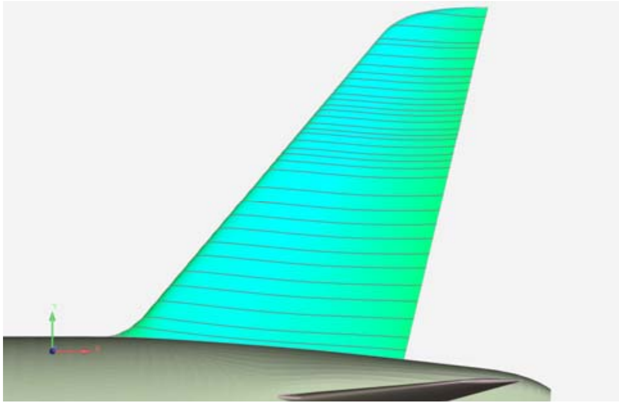

Fig. 11. Current lines on the fin in cruising mode

All mentioned above shows us the opportunity of local aerodynamic defect rectifying with VGs. Nevertheless, prevention of these defects at the stage of aerodynamic design is the best solution. It is not always possible, and the presence of VGs on the aircraft tells us, that the constructor knows that there are issues in local aerodynamics and takes an active approach towards them.

Conclusion

Thus, the following should be noted. The use of VGs to facilitate the aircraft take-off and landing characteristics is appropriate in case of separation area presence on the surfaces in flight operation modes. The effect from VG use on aircraft may appear in case of them being set on the engine nacelle, upper flap surface, in the tail unit. Types of VGs, their geometrical and setting parameters should provide emergence of stable vortex harnesses, leading to "postponing" the friction boundary layer separation on the lifting surfaces.

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Information about the authors

Vladimir G. Tsipenko, Doctor of Technical Sciences, Professor of the Aerodynamics, Airframe and Strength of Aircraft Chair, Moscow State Technical University of Civil Aviation, avas38@yandex.ru.

Mikhail V. Sagaydak, IRKUT Corporation Regional Aircraft Branch, mikhaelvs@mail.ru.

Vladimir I. Shevyakov, Doctor of Technical Sciences, the Head of the Aerodynamics Performance Department, IRKUT Corporation Regional Aircraft Branch, shevvi@mail.ru.

Сведения об авторах

Ципенко Владимир Григорьевич, доктор технических наук, профессор кафедры аэродинамики, конструкции и прочности летательных аппаратов МГТУ ГА, avas38@yandex.ru.

Сагайдак Михаил Вадимович, старший специалист департамента аэродинамических характеристик ПАО «Корпорация "Иркут"», филиал «Региональные самолеты», mikhaelvs@mail.ru.

Шевяков Владимир Иванович, доктор технических наук, начальник департамента аэродинамических характеристик ПАО «Корпорация "Иркут"», филиал «Региональные самолеты», shevvi@mail.ru.

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