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2.5.12 – Аэродинамика и процессы теплообмена летательных аппаратов;
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2.5.14 – Прочность и тепловые режимы летательных аппаратов;
2.5.15 – Тепловые электроракетные двигатели и энергоустановки летательных аппаратов;
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Investigation of the influence of engine displacement along the aircraft wing on the propagation of a condensation trail

A.I. Zhelannikov[1], A.N. Zamyatin[2]
[1]*Central Aerohydrodynamic Institute, Zhukovsky, Russia*
[2]*Gromov Flight Research Institute, Zhukovsky, Russia*

Abstract: With the publication of this article, the authors continue their research into the interaction of vortex and condensation trails behind aircraft, which has begun in the previously published articles in the Civil Aviation High Technologies of the Moscow State Technical University of Civil Aviation. This paper presents the investigation results of the influence of engine displacement along the A320 aircraft wing on the development and propagation of a contrail. It should be clear that a contrail is a product of aviation fuel combustion in the engine and represents condensed moisture in the form of ice crystals, which is formed under certain conditions of the atmosphere. As numerous studies and observations have shown, contrails can affect the heat exchange processes in the atmosphere and deteriorate the environment contributing to the greenhouse effect. This is especially true for the areas where numerous airways pass. It was noted that inboard engine displacement or, vice versa, outboard affects the development and propagation of a contrail. Therefore, when forming the aerodynamic configuration of the future aircraft, designers should take this aspect into account. The fact is that a wake vortex, which is formed behind the aircraft, impacts the contrail in different ways, depending on the engine proximity to the vortices, trailing from the airframe. Let us point out that a wake vortex is the area of the disturbed airflow behind the aircraft, generated as a result of its movement. A contrail, interacting with a vortex one, dissipates in the atmosphere, and the substances, composing a contrail, lose their concentration. It is also significant that a contrail, interacting with a wake vortex, can reveal its structure and visualize the wake vortex propagation and decay processes. In this paper, a special computational software application, based on the discrete vortex method, was used to study the influence of engine displacement along the A320 aircraft wing on the development and propagation of a contrail. When calculating the characteristics of a wake vortex, it takes into consideration the aircraft weight, speed and altitude, flight configuration, ambient conditions, axial velocity in the vortex core and some other factors. This complex passed the required testing and the state registration. A variety of activities was undertaken to validate and verify the developed complex, confirming the operability of its programs and the reliability of the results obtained. The results obtained allow us to understand how engine displacement along the A320 aircraft wing influences the contrail development and propagation.

Key words: engine displacement, condensation trail, wake vortex, aircraft, interaction of trails.

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Исследование влияния смещения двигателя по крылу воздушного судна на распространение конденсационного следа

А.И. Желанников[1], А.Н. Замятин[2]
[1]Центральный аэрогидродинамический институт имени проф. Н.Е. Жуковского, г. Жуковский, Россия
[2]Летно-испытательный институт имени М.М. Громова, г. Жуковский, Россия

Аннотация: Публикацией данной статьи авторы продолжают исследования взаимодействия вихревого и конденсационного следов за воздушными судами, начатые в ранее опубликованных статьях в «Научном Вестнике МГТУ ГА». В данной работе приводятся результаты исследования влияния смещения двигателя по крылу самолета А-320 на развитие и распространение конденсационного следа. Напомним, что конденсационный след является продуктом сгорания авиационного топлива в двигателе и представляет собой сконденсированную влагу в виде ледяных кристаллов, которая образуется при определенных состояниях атмосферы. Как показали многочисленные исследования и наблюдения, конденсационные следы могут влиять на теплообменные процессы в атмосфере и, способствуя парниковому эффекту, ухудшать экологию. Особенно это актуально для местности, где проходят многочисленные воздушные транзитные трассы воздушных судов. Было замечено, что смещение двигателя по крылу ближе к фюзеляжу или, наоборот, дальше от фюзеляжа влияет на развитие и распространение конденсационного следа. Поэтому при формировании аэродинамической компоновки будущего самолета конструкторам надо учитывать и этот аспект. Дело в том, что вихревой след, образующийся за воздушным судном, по-разному воздействует на конденсационный след в зависимости от близости двигателя к вихрям, сходящим с планера самолета. Заметим, что вихревой след – это область возмущенного воздушного потока за самолетом, образующаяся в результате его движения. Конденсационный след, взаимодействуя с вихревым, рассеивается в атмосфере, а вещества, входящие в состав конденсационного следа, теряют свою концентрацию. Отметим также, что конденсационный след, взаимодействуя с вихревым следом, может выявлять его структуру, а также визуализировать процессы распространения и затухания вихревого следа. В данной работе для исследования влияния смещения двигателя по крылу самолета А-320 на развитие и распространение конденсационного следа был использован специальный расчетно-программный комплекс, базирующийся на методе дискретных вихрей. В нем при расчете характеристик вихревого следа учитываются полетный вес, скорость и высота полета самолета, его полетная конфигурация, атмосферные условия, осевая скорость в ядре вихря и некоторые другие факторы. Этот комплекс прошел необходимую апробацию и государственную регистрацию. Был выполнен ряд мероприятий по валидации и верификации разработанного комплекса, подтверждающих работоспособность программ, входящих в него, и достоверность получаемых результатов. Получены результаты, которые позволяют понять, как влияет смещение двигателя по крылу самолета А-320 на развитие и распространение конденсационного следа.

Ключевые слова: смещение двигателя, конденсационный след, вихревой след, воздушное судно, взаимодействие следов.

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Introduction

The given article is a logical continuation of the previously published paper [1]. Thus, in order not to refer a reader to the content of these papers, there will be rather a small selective paper review on the given pages [1]. It has been done for better insight into the article integrity. So, what is a contrail? By fuel combustion in the engine nozzle exit, there is water vapor among other combustion gases. Under specific conditions of the atmosphere, this vapor together with atmospheric moisture become condensed in the form of drops, ice crystals and visible [2]. This is a contrail. As the numerous research and observations have shown, with the lapse of time, contrails transform into shallow cirrus and can affect the Earth's climate as well as the atmospheric heat exchanging processes. They contribute to the carbon dioxide effect and deteriorate environment. It is particularly topical for the areas with intensive air traffic and numerous airways. Currently, various techniques to reduce or even remove a contrail are being developed. For example, if to use ultra-low sulfur fuel, as the authors claim, it is practicable to remove a contrail almost completely (US Application № 12/614,640 dated from November 9^{th}, 2009). The alternatives for flight altitude changes and rerouting are also considered, but these solutions can result in increase in flight time, subsequently, the additional CO_2 emissions. A local increase in CO_2 can cause acid rains [2]. The known papers [3–5] investigate aircraft vortex and contrails. These studies have shown that contrails generated by aircraft of modern aerodynamic configurations like the A320 type are drawn into a wake vortex, and their further propagation in the atmosphere depends on a variety of factors, i. e., airspeed and altitude of flight, aircraft aerodynamic and in-flight configurations, as well as atmospheric conditions under which a flight is performed [6–12]. The paper [6] illustrates that the aerodynamic configuration of some aircraft can have a favorable effect on the contrail propagation from the point of view of its dispersion in the atmosphere. The engines of these aircraft are installed short of the wing tip, hence, the tip vortices, trailing from the wing, capture a contrail and disperse it partially or fully, therewith, decreasing its adverse impact on environment.

However, there seem to be possible to understand the way of interacting vortex and contrails regarding a new aircraft in advance, on the stage of a new aircraft design. By means of installing engines inboard or outboard, the optimal engine arrangement can be ensured considering the dispersion of a contrail in the atmosphere.

This article investigates the influence of engine displacement along the A320 aircraft wing on the contrail development and propagation. The A320 aircraft was chosen intentionally as an object of study. This type is operated all over Russia and worldwide.

Research methodology

Research into the influence of engine displacement along the A320 aircraft wing on the development and propagation of a contrail was conducted using the computational software application [13], which basic principles and concepts are described in the monographs [3, 14] and articles [15–19].

The basics of the computational software application is a mathematical model of the far field wake vortex [3], in which velocities, disturbed by an aircraft, were obtained based on an accurate solution of the Helmholtz equation [20]. This allowed us to consider the dissipation and diffusion of vortices, modeling a wake vortex. These phenomena are associated with the natural process of vortices decay in the meteorological atmosphere. The contrail was modeled in the following way: four markers, which simulated the contrail boundary, were located around the engine nozzle contour. Another marker was placed in the center of the nozzle. The markers were considered weightless. The problem was solved in a nonlinear nonstationary setting by the method of discrete vortices. The markers moved in space within the time frame, considering the aircraft wake vortex effect. The problem was solved in the dimensional format; therefore, the graphs below show computational data for the A320 aircraft specific flight conditions.

To assess an ambient condition, the mathematical model of the far field wake vortex of the computational software application, used the Richardson number Ri. The Richardson number characterizes the ratio of the buoyancy forces (numerator) and dynamic factor (denominator), that is, the ratio of the free and forced convection contributions to the formation of atmospheric turbulence. Hence, the temperature gradient modulus increase corresponds to the state under which the buoyancy forces dominate. The velocity gradient increase corresponds to the dynamic factor increase and characterizes the atmosphere as unstable. The ambient condition is considered neutral if $-0.01 \leq Ri \geq 0.01$, concurrently, the thermal effect is minimal, and in this case only

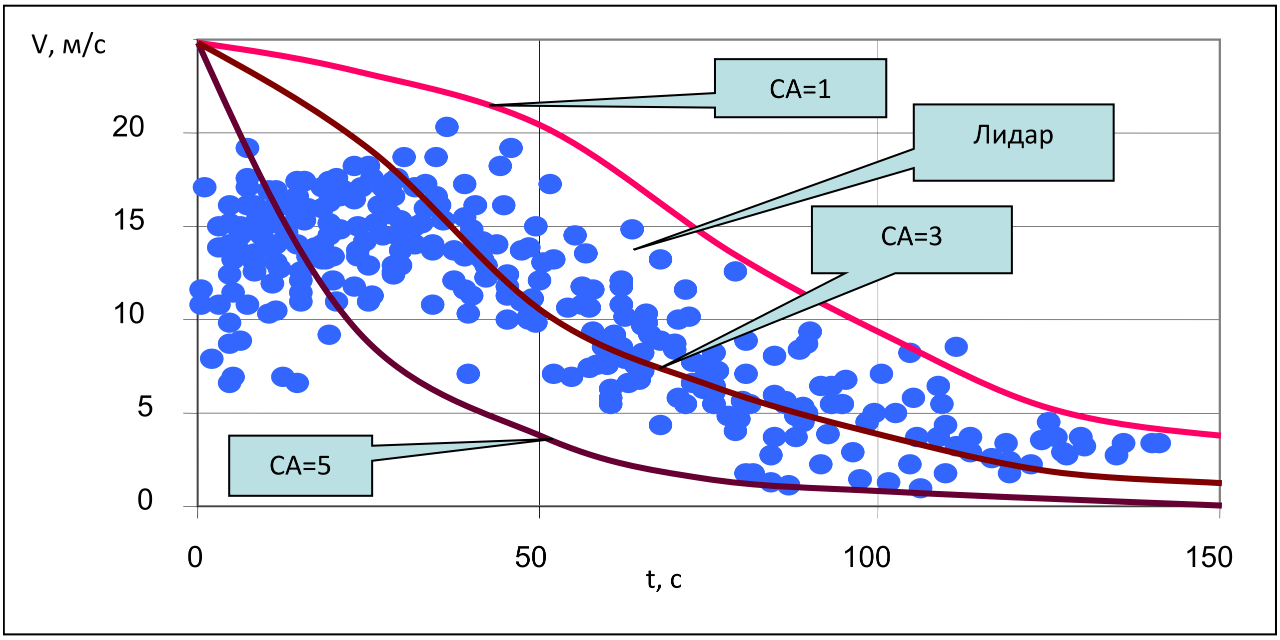

Fig. 1. Dependence of the B-747 aircraft maximum speed in the core on the time of vortex arrival towards a lidar

forced convection can exist. When the $Ri < -0.01$ number decreases, the buoyancy forces begin to manifest themselves more, the mixed convection emerges, and at $Ri < -1.0$, a free convection mode is established. On the contrary, with an increase in $Ri > 0.01$, the buoyancy forces begin to prevent the turbulence development. At $Ri > 0.25$, the current becomes almost laminar, the turbulent mixing is virtually not available. Thus, at $Ri < -1.0$, the ambient condition is considered highly unstable (AC = 5), at $-0.01 > Ri \geq -1.0$ – unstable (AC = 4), at $0.01 \geq Ri \geq -0.01$ – neutral (AC = 3), at $2.5 \geq Ri > 0.01$ – stable (AC = 2) and at $Ri > 0.25$ – highly stable (AC = 1).

Testing of the ambient condition assessment in the context of vortices decay velocity, trailing from an aircraft, was completed. For this purpose, the experimental results were used to measure the B-747 aircraft maximum airspeed in the vortices, obtained at the airport of Frankfurt on the Main by a lidar, and excerpted from the Ph.D. dissertation by G.G. Sudakov (fig. 1). Using the circles, it illustrates the results of measurement of the B-747 aircraft maximum airspeed V in the vortices by means of a lidar depending on time t of vortex arrival towards a lidar. Within the timespan, vortices, trailing from the B-747 aircraft wing depending on the ambient condition, alleviate their intensity, and a maximum speed V reduces. The lines in Figure 1 are the computation by the computational software application [15] of the B-747 aircraft maximum speed in the vortices under various ambient conditions: AC = 1 – strongly stable, AC = 3 – neutral and AC = 5 – strongly unstable. We can see that the results of measurement of the B-747 aircraft maximum speed in the vortices are almost completely located between the lines AC = 1 and AC = 5, which implicitly refers to feasibility of the mathematical models integrated into the computational software application [15] and validity of its results.

Research results

The A320 aircraft was chosen as an object of study. The altitude of flight came to H = 10000 m, airspeed V = 850 km/h, the behind-the-aircraft distance up to which vortex and contrails were computed, made 30 km. The A320 aircraft flight weight came to 77 tones. Let us note that, the ambient condition, in the computations, was introduced as neutral (AC = 3). In the graphs below, all the linear dimensions are made on the

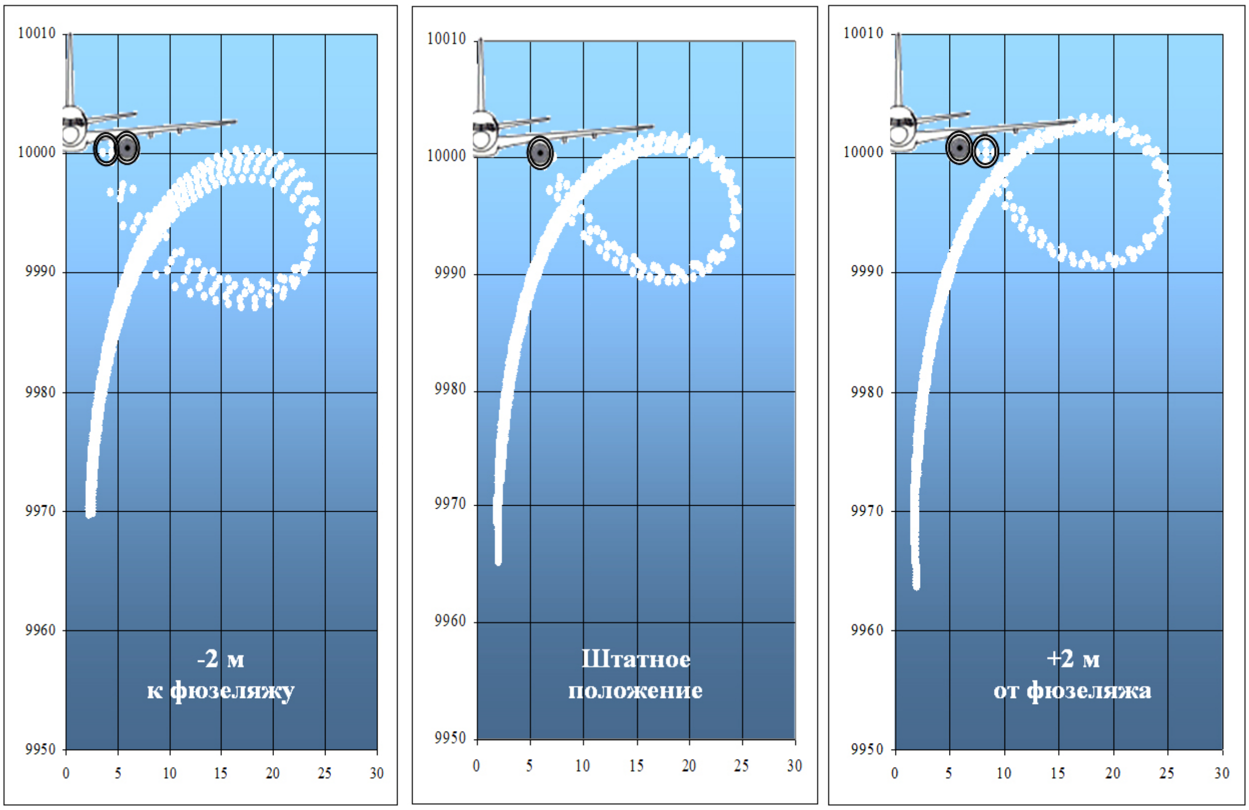

Fig. 2. Influence of engine displacement along the A320 aircraft wing on the contrail development, V = 850 km/h, H = 10000 m

same scale for the convenient perception. Figure 2 represents the computation results of a contrail for three cases of engine location on the A320 aircraft wing: the conventional position and displacement of engine by −2 m towards the fuselage and +2 m from the one.

The graph axes are shown in meters in Figure 2. The vertical axis is a flight altitude H, the horizontal one is the axis Z associated with the aircraft by the system of coordinates. It appears that even insignificant engine displacement along the A320 aircraft wing influences profoundly the contrail propagation. It can be explained if to look at the contrail propagation behind the A320 aircraft (fig. 3). It represents the fields of perturbation velocities in the distance X = 0.500, 1000 и 1500 m from the aircraft. The red line is the velocity scale 10 m/s. The computational mesh is 3, 2 × 2 m in the Figure. Figure 4 shows the computational results of the contrail position behind the A320 aircraft in the coordinates H(X): H – the flight altitude in meters, X – the distance behind the aircraft in kilometers.

Figure 4 also illustrates that engine displacement along the aircraft wing significantly influences on the contrail propagation.

The mathematical model of the far field wake vortex, integrated into the computational software application [15], makes it possible to perform the contrail computation in the context of further engine displacement to the wingtip. Figure 5 shows the results of the contrail computation behind the A320 aircraft when an engine is displaced by +3 m, +5 m, +8 m towards the wingtip from the conventional position. The graphs axes are shown in meters in Figure 5.

We can see that further engine displacement towards the wingtip also leads to the variation of the contrail propagation.

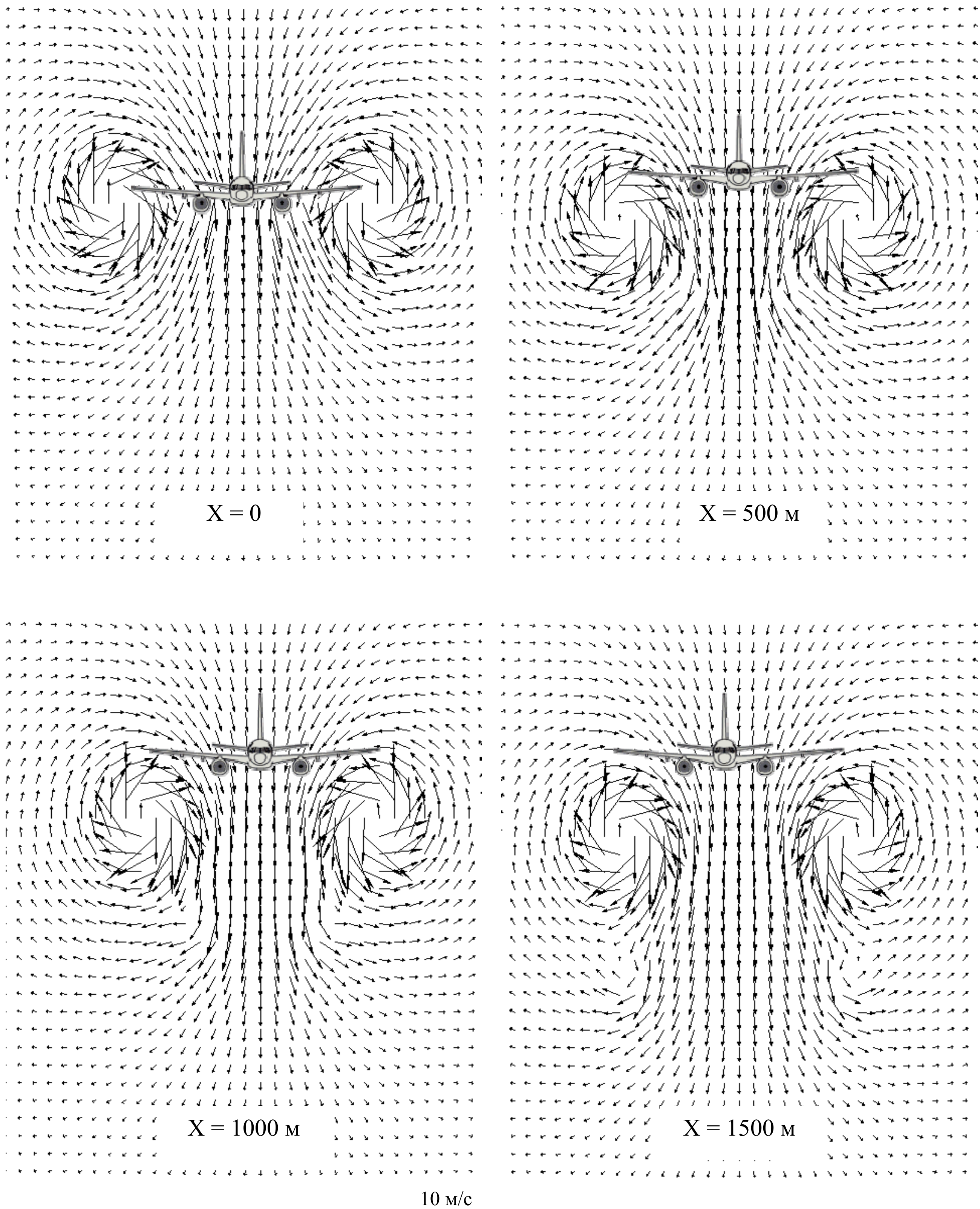

Fig. 3. Wake vortex development behind the A320 aircraft,
V = 850 km/h, H = 10000 m

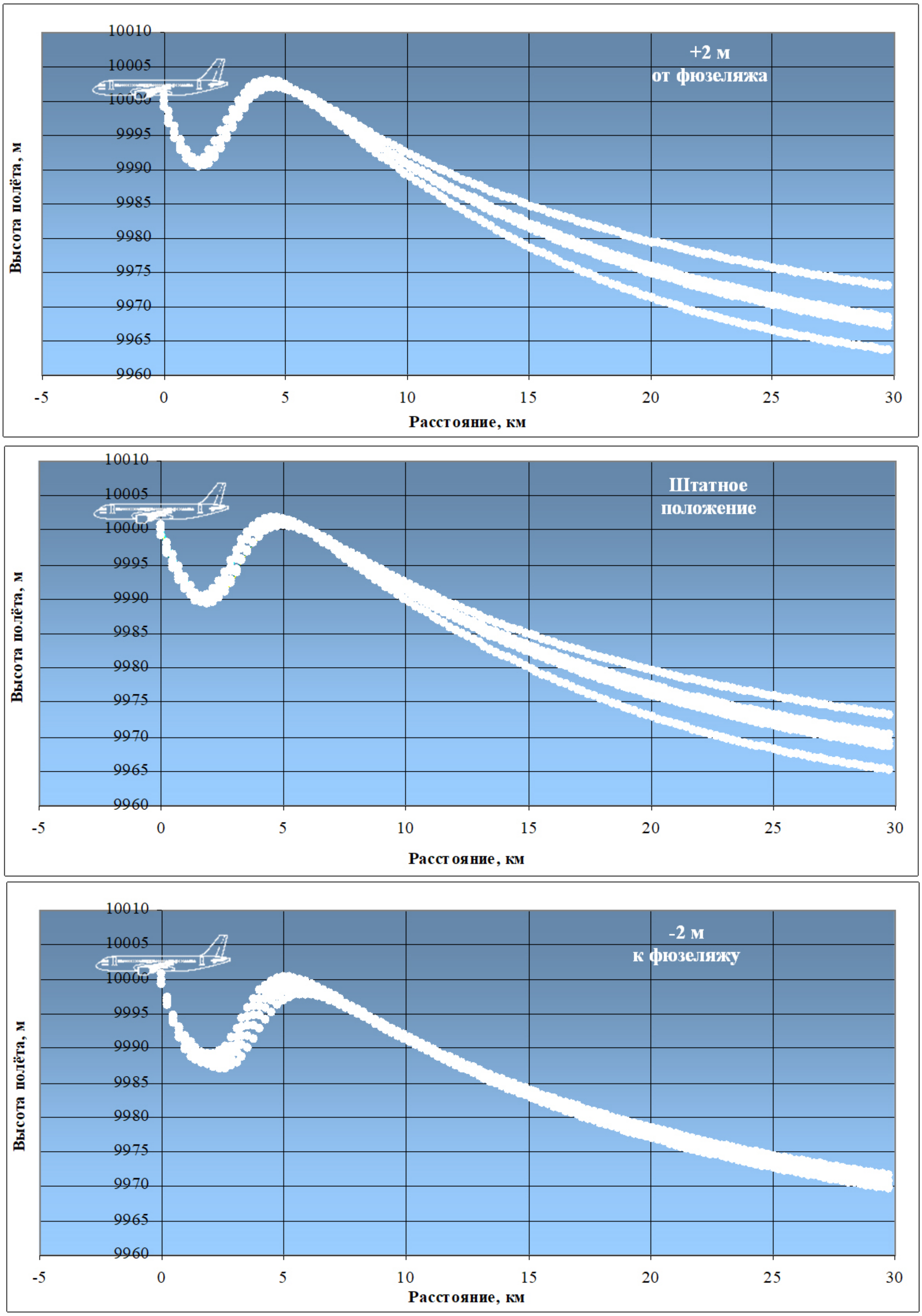

Fig. 4. Influence of engine displacement along the A320 aircraft wing on the contrail development, V = 850 km/h, H = 10000 m

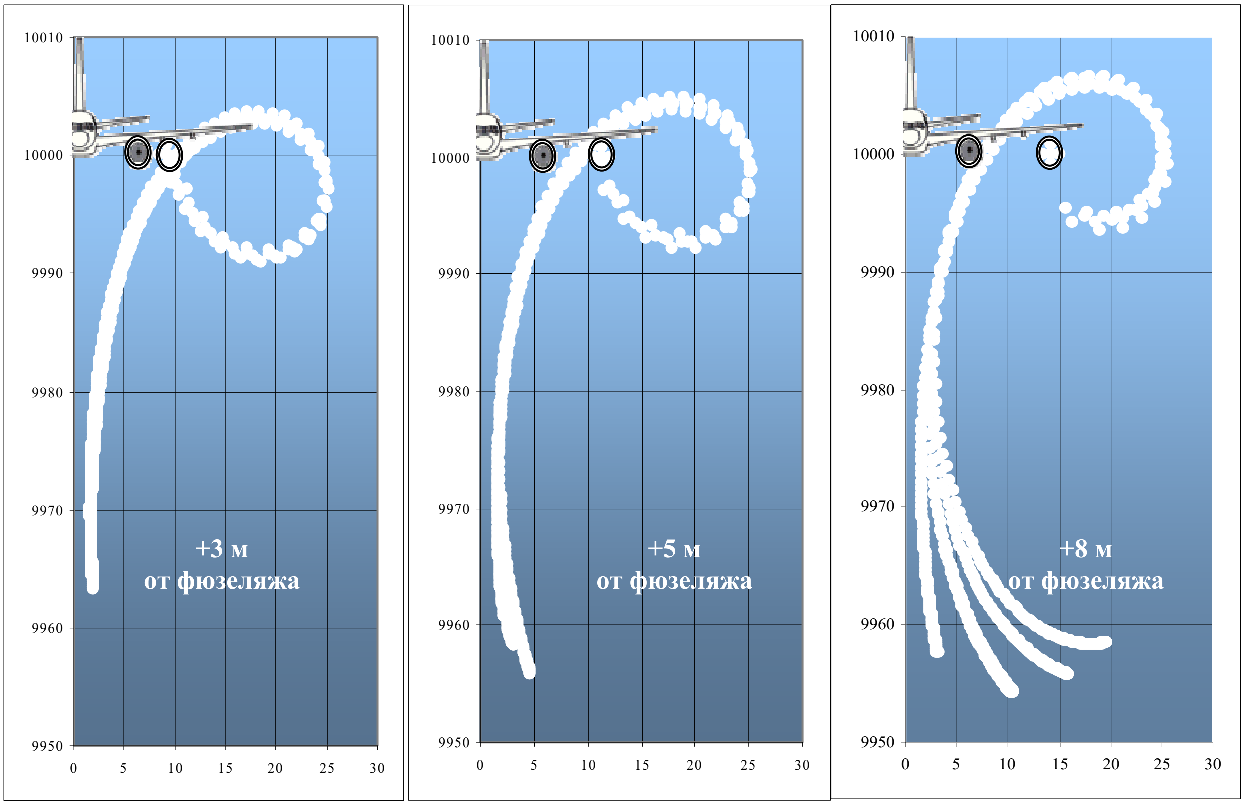

Fig. 5. Influence of engine displacement along the A320 aircraft wing on the contrail development, V = 850 km/h, H = 10000 m

Conclusions

Sum up: the computations showed that contrails propagation behind aircraft substantially depends on engine arrangement on the aircraft wing. Thereupon, if to conduct investigations with respect to optimal engines location on the aircraft wing in the context of the wake vortex impact on the contrail in advance, on the stage of a new aircraft design, we can mitigate a negative effect on environment. A wake vortex, interacting with a contrail, dissipates the latter in the atmosphere decreasing the concentration of substances.

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Information about the authors

Alexander I. Zhelannikov, Doctor of Technical Sciences, Professor, Chief Researcher of Central Aerohydrodynamic Institute, zhelannikov@yandex.ru.

Andrey N. Zamyatin, Candidate of Technical Sciences, Senior Researcher, Head of the Department of Gromov Flight Research Institute, (FRI), frizamyatin@mail.ru.

Сведения об авторах

Желанников Александр Иванович, доктор технических наук, профессор, главный научный сотрудник ЦАГИ им. проф. Н.Е. Жуковского, zhelannikov@yandex.ru.

Замятин Андрей Николаевич, кандидат технических наук, старший научный сотрудник, начальник отделения ЛИИ им. М.М. Громова, frizamyatin@mail.ru.

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