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Reducing take-off and landing distances for regional turboprop aircraft

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Abstract: The increased efficiency of turboprop engines in cruising flight as well as low operating costs have determined the economic feasibility of using regional propeller-driven aircraft to transport 40–80 passengers on short routes within one country or connecting two nearby regions (for example, in Russia). The aerodynamic performance requirements for regional aircraft, determined from typical flight missions for the Russian and European markets differ greatly in range and required runway lengths. The typical flight range in Europe is about 800 km, while in Russia it increases to 1500 km due to the limited number of airports and aerodromes in operation. The limitation on runway length is 1300 m (airfield class G) for aircraft with a maximum take-off weight and 1000 m (class D) with a payload of up to 70% of the maximum value. The ability to take off and land from unpaved runways is also an essential requirement in Russia. This leads to a more complex design and an increase in the weight of the airframe, as well as to the need to increase the wing lift. Most of the operating European regional aircraft previously did not have tight restrictions on runway lengths and their takeoff and landing characteristics were not active constraints when forming wing configurations. However, the recently observed growing demand for air travel leads to a significant increase in the load on hub airports and, as a result, to the delay of many flights. One of the possible ways to solve this problem is to relieve the major hub airports by transferring regional aircraft service to nearby local airports. This will require both the modernization of existing airports and the development of a new generation of aircraft with short takeoff and landing distances (STOL). The development of STOL aircraft which are capable of connecting local airports and small towns has been conducted for many years. The STOL performance can be achieved by both developing an effective high-lift system with increased lift effectiveness and wing load alleviation. Wing load alleviation, often used in the light aircraft transitional category, leads to deterioration of cruising performance and increased sensitivity to atmospheric turbulence, especially at low altitudes. This makes difficult to track the final approach paths when controlling the pitch angle by deflecting the elevator. Therefore, a more preferable and more often considered option to reduce takeoff and landing distances of commercial airplanes is the increase of lift performance in combination with a set of additional technical solutions. Significant advances in the application of computational techniques for the development of swept wing high lift devices for long-haul aircraft with high lifting properties ($Cy_{max} \approx 3$), including a retractable Fowler flap and a three-position slat, make it possible to use a similar approach to the design of high-lift system for new regional aircraft. Taking into account the specifics of aircraft operation at local aerodromes, a complex of technical solutions has been considered to increase wing lift at low flight speeds, as well as additional measures to reduce the landing distance. The results of computational and experimental studies of the proposed technical solutions are presented with an assessment of the effectiveness of their use on a regional aircraft of the ATR 42-600 type.

Key words: regional aircraft, high-lift wing design, lift control, steep glide path, STOL.

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Сокращение дистанций взлета и посадки региональных турбовинтовых самолетов

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Аннотация: Повышенная эффективность турбовинтовых двигателей в крейсерском полете, а также небольшие эксплуатационные расходы определили экономическую целесообразность применения региональных винтовых самолетов для перевозки 40–80 пассажиров на коротких маршрутах в пределах одной страны или близлежащих регионов (например, в России). Аэродинамические требования к характеристикам региональных самолетов, определяемые из типичных миссий полета для российского и европейского рынков, заметно отличаются по дальности и условиям базирования. Типичная дальность полета в Европе составляет около 800 км, в то время как в России возрастает до 1500 км вследствие ограниченного количества эксплуатируемых аэропортов и аэродромов. Ограничением по условиям базирования является длина взлетно-посадочной полосы (ВПП) 1 300 м (класс аэродромов Г) для самолетов с максимальной взлетной массой и 1 000 м (класс Д) с полезной нагрузкой до 70 % от максимального значения. Также существенным требованием в России является возможность взлета и посадки с грунтовых ВПП. Последнее приводит к усложнению конструкции и увеличению веса планера, а также необходимости повышения несущих свойств крыла. Большинство эксплуатируемых европейских региональных самолетов ранее не имели жестких ограничений по условиям базирования, и их взлетно-посадочные характеристики не были активными ограничениями при формировании компоновок крыла. Однако наблюдаемый в последнее время растущий спрос на воздушные перевозки приводит к существенному увеличению нагрузки на узловые аэропорты и, как следствие, к задержке многих рейсов. Одним из возможных способов решения этой проблемы является разгрузка крупных аэропортов за счет переноса обслуживания региональных самолетов на близлежащие пригородные аэродромы. Это потребует как модернизации существующих аэропортов, так и разработки нового поколения самолетов с короткими дистанциями взлета и посадки (КВП). Разработка самолетов КВП, способных связывать пригородные аэропорты и небольшие населенные пункты, ведется уже в течение многих лет. Характеристики КВП могут быть обеспечены как за счет разработки эффективной системы механизации с повышенным уровнем несущих свойств, так и снижения нагрузки на крыло. Снижение нагрузки на крыло, часто используемое в переходной категории легких самолетов, приводит к ухудшению крейсерских характеристик и повышению чувствительности к атмосферной турбулентности, особенно на малых высотах полета. Последнее затрудняет отслеживание траектории конечного этапа захода на посадку при управлении углом тангажа посредством отклонения руля высоты. Поэтому более предпочтительным и чаще рассматриваемым вариантом сокращения взлетно-посадочных дистанций коммерческих самолетов является повышение несущих свойств крыла в сочетании с набором дополнительных технических решений. Значительные успехи в применении численных методов для разработки механизации стреловидного крыла магистральных самолетов с высоким уровнем несущих свойств ($Cy_{max} \approx 3$), включающей выдвижной закрылок Фаулера и трехпозиционный предкрылок, позволяют использовать аналогичный подход к проектированию механизации крыла новых региональных самолетов. С учетом специфики эксплуатации самолетов на пригородных аэродромах рассмотрен комплекс технических решений, предназначенных как для увеличения несущих свойств крыла при малых скоростях полета, так и дополнительных мер для сокращения посадочной дистанции. Приведены результаты расчетных и экспериментальных исследований предложенных технических решений с оценкой эффективности их применения на региональном самолете типа ATR 42-600.

Ключевые слова: региональный самолет, проектирование высоконесущего крыла, управление подъемной силой, крутая глиссада, КВП.

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Introduction

Currently, the leaders in the production of regional propeller aircraft are the Franco-Italian concern ATR and the Canadian Bombardier Aerospace [1]. ATR produces aircraft of the ATR42 and ATR-72 series, Bombardier produces aircraft of the Dash 8 Q-400 series. Aircraft of both series have a typical configuration with a high-mounted wing of increased aspect ratio ($\lambda \approx 12$), a narrow cylindrical fuselage, a single-fin T-shaped tail unit and engines installed under the wing [2]. In the absence of tight restrictions on runway lengths, their takeoff and landing characteristics were not active limitations when forming wing layouts. This caused a moderate level of wing lifting properties at low flight speeds ($Cy_{max} \approx 2.5$) and increased takeoff and landing distances: takeoff – 1107 m, landing – 966 m (ATR 42-600 aircraft)[1].

The recently observed growing demand for air transportation leads to a significant increase in the load on hub airports, and, as a result, to the delay of many flights. One of the possible solutions to this problem is to relieve large airports by transferring regional aircraft service to nearby local aerodromes [3, 4]. A necessary condition for relieving hub airports is the modernization of the infrastructure of existing local airports, as well as the construction of new aircraft with short takeoff and landing distances. In the short-term a possible option may also be a modernization of existing aircraft in order to improve the

1 ATR 42-600. atr-aircraft.com. Available at: https://www.atr-aircraft.com/aircraft-services/aircraft-family/atr-42-600/ (accessed: 07.12.2023).

lifting properties of the wing. The transfer of small regional aircraft to local airports will free up long runways at hub airports to handle larger aircraft and will increase both passenger traffic and the capacity of the entire transport system.

In Russia, with the share of regional air transportation estimated at 10% of the entire air transport network, one of the key economic tasks is to ensure an acceptable transport network in the near future. The specific requirements for regional aircraft flights for the Russian and European markets lead to differences in flight range and runway lengths [5]. Thus, restrictions on the number of airports and aerodromes in operation increase the typical flight range to ~1500 km, against ~800 km in Europe. An additional requirement for runway lengths on unpaved aerodromes complicates the airframe design and requires an increase in the wing lifting properties due to the complexity of the high-lift system. For the new regional aircraft being developed, it is proposed to ensure takeoff/landing with a maximum takeoff weight from a runway of up to 1300 m (airfield class G) and a reduced payload by 30% from a runway of up to 1,000 m (airfield class D).

The aerodynamic requirements for the wing lifting properties of STOL aircraft, as well as the stability and controllability characteristics at low flight speeds of the aircraft are considered in works [6, 7]. To achieve short takeoff distances, the aircraft must either take off at a very low speed or use a sufficiently high level of thrust or power-to-weight ratio to achieve takeoff speed at the required distance. The landing distance reduction is achieved due to a short airspace segment using a steep approach path and minimizing the landing ground roll at the minimum possible speed and ensuring maximum deceleration using an effective braking system.

Some airports require steep aircraft approach in mountainous areas or in urban environments with nearby high buildings. In 2016, Embraer certified the Legacy 500 for a steep approach of 5.5°[2], allowing the aircraft to operate at London City Airport.

Taking into account the specifics of aircraft operation at local aerodromes, the paper considers a set of technical solutions for reducing takeoff and landing distances for regional aircraft, including:

- development of new high-lift wing profiles that determine the initial Cy_{max} value of an aircraft with retracted high-lift system at low flight speeds,
- design of adaptive trailing edge high-lift system with integration of flap extension with downward deflection at small spoiler angles,
- design of a simplified version of the leading edge high-lift system in the form of a rotary slotted Krueger,
- ensuring a steep approach path with direct control of the wing lift (DCL) as a result of spoiler deflection, including upward to reduce the lifting properties,
- evaluation of the use of automatic spoiler release to reduce the landing distance.

The effectiveness of the proposed technical solutions to reduce takeoff and landing distances for regional aircraft was assessed by calculations on a regional aircraft of the ATR 42-600 type.

Critical parameters affecting aircraft takeoff and landing distances

There is a connection between the selection of wing parameters based on cruising flight conditions and their subsequent influence on the high-lift system design which is necessary to achieve the required level of lift-to-drag ratio (L/D ratio) of the aircraft in takeoff and landing modes. Thus, a wing area reduction has a positive effect on cruising characteristics, but at the same time requires the use of a more complex system for increasing the wing lift.

The requirements for the wing L/D ratio in takeoff and landing modes are determined by various limitations, such as takeoff and landing weight, required runway length, climb gradient and approach speed. There are correlations between the influence of aerodynamic, weight and

[2] Flexjet demonstrates London steep approach with Legacy500. truenoord.com. Available at: https://www.truenoord.com/wpcontent/uploads/2023/12/LARA-December-2023.pdf (accessed: 07.12.2023)..

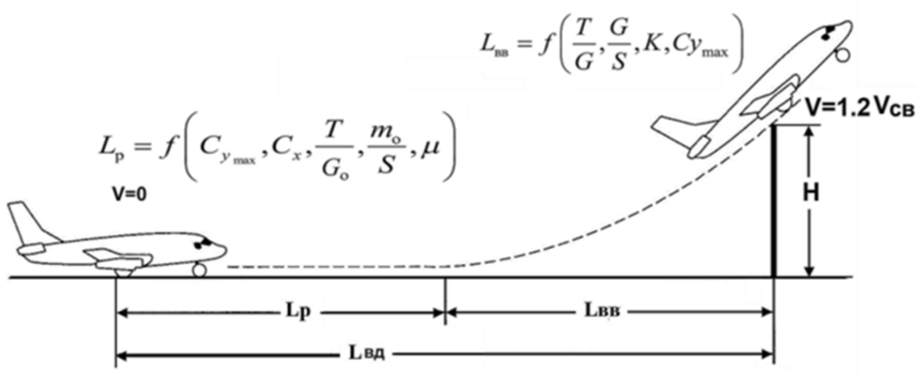

Fig. 1. Main sections of the take-off distance

thrust characteristics of the power plant with takeoff and landing distances and safe flight speed for aircraft flight conditions with deflected wing high-lift system.

A simplified version of the aircraft takeoff distance presentation (fig. 1) includes the lengths of the takeoff roll (L_r) and the airspace segment (L_{as}). The length of the takeoff roll depends on the thrust-to-weight ratio ($T / G_о$), determined by the ratio of the static thrust to the takeoff weight at sea level, the takeoff wing loading ($G_о / S$), determined by the ratio of the takeoff weight to the wing area, and the takeoff value Cy_{max}, which normalizes the aircraft liftoff speed from the runway. Aircraft drag (Cx) and the coefficient of rolling friction (μ) also have an effect. The angle of climb, which determines the distance required to overcome the obstacle clearance height (H), depends on the thrust-to-weight ratio ($T / G_о$), wing loading, aerodynamic quality (Q) and takeoff value Cy_{max}, which determines the safe speed at the end of the air leg *($V = 1.2V_{as}$)*. The minimum climb gradient (θ) must be maintained even in the case of one engine failure. To minimize the takeoff distance, it is necessary to maximize the aerodynamic parameters Cy_{max} and Q, while the drag and $G_о / S$ should have minimal values.

A simplified version of the aircraft landing distance (fig. 2) includes the lengths of the air leg (L_{as}) and the landing roll (L_r). The approach speed *($V = 1.3V_{as}$)*, which determines the descent angle θ, depends on the landing value Cy_{max}, the aerodynamic quality (Q) and the wing loading *(G_L/S)*. For a steep approach path, the descent angle must be greater than the minimum value of 3°, required by aviation regulations. The ground roll is a function of the aircraft speed at the moment of touchdown (i.e. Cy_{max}), and also depends on the efficiency of the braking system (μ_b), spoilers for “damping” the wing lift during the landing roll and the power plant thrust reverser (T_r). To reduce the landing distance, it is necessary to maximize the value Cy_{max}, to reduce the approach speed, while minimizing the values of the aerodynamic quality and the wing loading. However, the desire for high aircraft drag in the landing configuration may conflict with the required climb gradient during the go-around.

In addition to the general requirement to ensure a high-lift wing in takeoff and landing modes, the work [8] indicates the priority of the aerodynamic quality value at takeoff and the maximum lift coefficient for landing. Also, the characteristics of the high lift wing must meet the requirements of aircraft controllability at high angles of attack. For this purpose, the choice of geometric parameters and the position of the high lift devices is carried out based on the condition of ensuring priority in the occurrence and development of flow separation from the wing root. The increments of the pitch moment for a dive realized in this case reduce the angle of attack and restore the favorable nature of the flow around the wing. The separation-free nature of the flow around the wing tips ensures that the

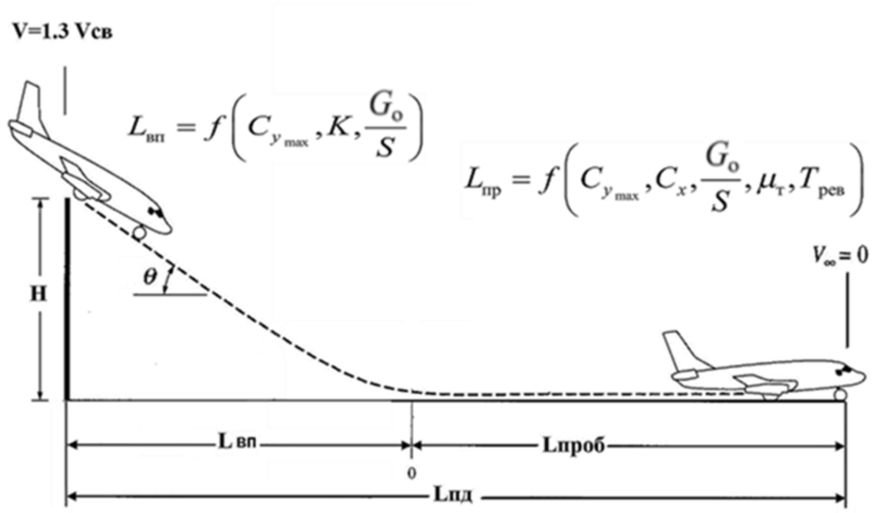

Fig. 2. Main sections of the landing distance

aircraft remains controllable in roll and eliminates wing stall.

The aircraft ability to be operated on short runways is also associated with ensuring the characteristics of safe controlled flight at low speeds. The minimum value of safe aircraft speed with deflected high lift devices is determined by the requirement to ensure the necessary efficiency of controls, including in critical flight modes. The first limitation on the value of minimum speed is the lateral and directional controllability of the aircraft, especially in the case of one engine failure. The second is longitudinal control at high lift coefficient values of the aircraft wing (C_y ~5 – STOL aircraft), which requires both an increase in the efficiency of the longitudinal control devices and the use of energy control methods.

Methodology for assessing the aerodynamic performance of the wing and aircraft takeoff and landing distances

The initial stage of designing high-lift system and assessing its effectiveness from the standpoint of the aircraft lifting properties and takeoff and landing distances is usually carried out under conditions of a limited amount of information on the wing configuration. The approach used to assess the lifting properties of the wing and the aircraft takeoff and landing distances is based on the semi-empirical methods given in study [9] for the conceptual design stage of the aircraft.

Estimation of C_{Ymax} values of the wing

For wing configurations with aspect ratio $\lambda \geq 8$, low sweepback and relative profile thickness c ≥ 9% the wing value Cy_{max_lan} in the landing configuration at low flight speeds ($M \leq 0.2$) is determined as the sum Cy_{max_w} of the wing values in the cruising configuration and the wing increment ΔCy_{max_lan} from the deflection of the high-lift devices

$$Cy_{max\_lan} = Cy_{max\_w} + \Delta Cy_{max\_lan}. \quad (1)$$

The value Cy_{max_w} is determined as half of the sum of the profile values Cy_{max} in the basic wing sections (root and tip) with corrections to account for the influence of the 3-dimensionality of the wing flow (coefficient K) and the sweepback estimated by the quarter chord of the wing ($\cos(\chi_{1/4})$)

$$Cy_{max\,w} = K\left(\frac{Cy_{max.r.pr} + Cy_{max.t.pr}}{2}\right)\cos(\chi_{\frac{1}{4}}). \quad (2)$$

To estimate the increment of the lifting properties of the wing in the landing mode (ΔCy_{max_w}), two-dimensional calculations of the flow around the wing sections with the high-lift devices retracted and deflected by the flow of viscous compressible gas are used within the framework of the Navier-Stokes equations averaged over Reynolds.

$$\Delta Cy_{max.w} = K \cdot \Delta Cy_{max} \cdot \left(\frac{S_{ser.fl.}}{S_w}\right) \cdot \cos\chi_{sw.fl.} \quad (3)$$

where ΔCy_{max} – Cy_{max} increment of wing sections from deflection of high lift devices,

$S_{ser.fl.}$ – relative wing area served by flaps,

$\cos\chi_{sw.fl.}$ – sweepback of flap leading edge.

The described method of estimating Cy_{max} values is applied to the wing of ATR 42-600 aircraft (fig. 3), in the configuration of which classic NACA430 series profiles with relative thicknesses of c = 18% (root) and 13% (tip) are installed. A double-slotted rotary flap with a fixed deflector and deflection angles is used as high lift devices of the trailing edge:

- $\delta_f = 15°$ – takeoff,
- $\delta_f = 25°$ – approach for landing,
- $\delta_f = 35°$ – landing.

Fig.3. Layout diagram of the ATR 42-600 aircraft

The evaluation of the lifting properties of the wing in the landing configuration ($\delta_f = 35°$) is performed on the basis of the cruising value of the coefficient $CY_{max} = 1.57$ and the calculated increment of the coefficient $\Delta CY_{max} = 1.0$ from the deviation of the high lift devices in the base sections of the wing, obtained in consideration with the wing area $S_{ser.fl.}/S_w = 0.64$ served by the flaps and the small sweep angle of their leading edge. A similar increment $\Delta CY_{max} = 0.49$ in the takeoff configuration ($\delta_f = 15°$) is determined from the condition of the linear nature of its change with regard to small and moderate deflection angles ($\delta_f < 30°$). The maximum level of values of the lift coefficient of the double-slotted rotary flap is realized at deflection angles $\delta_f = 45…50°$ with a nonlinear nature of behavior.

Thus, the predicted level of values Cy_{max} of the wing of the regional aircraft ATR 42-500 in takeoff and landing modes can be:

- $Cy_{max\_TO} = 1.99$,
- $Cy_{max\_lan} = 2.47$.

Estimation of takeoff and landing distances

The methodology for estimating the takeoff distance to an altitude of 35 ft (10.7 m), presented in work [9], is based on the use of a simple combination of three key aircraft characteristics to determine the takeoff distance: wing loading $(G/S)_{TO}$, weight-to-power ratio $(G/S)_{TO}$ and takeoff value of the coefficient Cy_{max} (C_{LmaxTO}).

$$L_{td} = (G/P)_{TO}/(0.0773 \cdot \sigma \cdot Cy_{max\,TO} \cdot F_{TO}), \text{ ft} \quad (4)$$

where σ (Δ) – the ratio of air density under takeoff conditions to the values at sea level under standard conditions t = 15° and p = 760 mm Hg (σ = 1),

F_{TO} ($\bar{N}$) – the ratio of takeoff power to the takeoff values at sea level ($F_{TO} = 1$)

$_{TO}$ – an index denoting the take-off (take-off) value of the ratio of the quantities indicated in brackets.

Table 1

Characteristics of the ATR 42-600 aircraft with the original wing

Standard configuration	**48 seats**
Engines Pratt & Whitney Canada	PW127M
Takeoff power, hp	2 × 2400
Propeller (AP) Hamilton Standard	568F
Number of blades	6
Propeller diameter, m	3.93
Maximum takeoff weight (MTOW), kg	18600
Maximum landing weight (MLW), kg	18300
Takeoff distance (MTOW, MCA, SL*), m	1107
Landing distance (MPW, MCA, SL), m	966

*SL – sea level.

Piloting techniques, aerodynamic drag and friction at takeoff are indirectly taken into account by the averaged empirical coefficient in formula (4).

The values of the variables in equation (4) are given in the British unit system. Taking into account the relationships 1 lb = 0.4535 kg and 1 ft = 0.30487 m, formula (4) takes the form (5)

$$L_{td} = 1.78\frac{(G_0/S)}{(N_0/G_0 \cdot Cy_{max} \cdot \Delta \cdot \bar{N}}, \text{ m.} \qquad (5)$$

The required runway length at takeoff for aircraft certified according to aircraft airworthiness standards-25 is determined by multiplying the takeoff distance by a safety factor of 1.15.

The landing distance is largely determined by the wing loading, which affects the approach speed and, according to aircraft airworthiness standards-25, must exceed the stall speed by at least 1.23 times for transport category aircraft. The approach speed, in turn, determines the landing speed, which must be "reduced" during the landing roll before the aircraft stops. Kinetic energy and, consequently, braking distance depend on the square of the landing speed and the efficiency of the aircraft braking system.

In work [9], expression (6) is presented for estimating the landing distance of an aircraft, based on the use of the two key aircraft characteristics: the wing loading and Cy_{max} coefficient (Cy_{max_L}) in the landing configuration.

$$L_L = 80 \cdot \left(\frac{G_l}{S}\right) \cdot \left(\frac{1}{\sigma \cdot Cy_{max_L}}\right) + L_{0,} \text{ ft}, \qquad (6)$$

where G_l/S – wing loading,

Cy_{max_L} – Cy_{max} coefficient in the landing configuration,

S_a – air leg length from a height of H = 15 ft.

S_a = 100 ft (305 m) for the glide path angle θ = 3° and 450 ft (137 m) for θ = 7°.

σ(Δ) – the ratio of air density under landing conditions to the values at sea level under standard conditions t = 15° and p = 760 mm Hg (σ = 1).

Taking into account the previously given relations between the British and technical systems of measurement units, formula (6) takes the form (7)

$$L_{L.d.} = 5 \cdot \left(\frac{G_L/S}{Cy_{max.L} \cdot \Delta}\right) + L_{as}, \text{ m} \qquad (7)$$

For most propeller-driven ATR aircraft, landing requirements must be met with a landing weight close to the takeoff value. A numerical estimate of the accuracy of determining takeoff and landing distances for the ATR 42-600 aircraft using the described methodology was carried out using the data given in Table 1 and a

Table 2

Calculated values of Cy_{max} and take-off and landing characteristics of the ATR 42-600 aircraft

Takeoff wing loading (G_o/S), kg/m^2	341.3
Power-to-weight ratio (N_o/G_o), hp/kg,	0.258
Cy_{max} coefficient (takeoff)	1.99
Takeoff distance (Lt.d), m	1177
Landing wing loading (G_{lan}/S), kg/m^2	335.8
Cy_{max} coefficient (landing)	2.47
Landing distance (Ll.d), m	985
Required runway length ($Lr = 1.43\ L_{l.d}$), m	1408

wing area of $S = 54.5$ m^2 (fig. 3), taken from the work[3].

The main parameters of the aircraft layout, the calculated values of the Cy_{max} coefficients and the corresponding takeoff and landing distances, as well as the required runway length, determined on the basis of European standards (safety factor 1.43) for turboprop aircraft[4], are given in Table 2.

The calculated values of the aircraft takeoff and landing distances (1177 and 985 m) are generally consistent with the similar characteristics of the aircraft (1107 and 966 m) given in Table 1.

Results and discussion

To relieve large airports by transferring regional aircraft service to nearby local aerodromes requires the development of a new generation of aircraft with short takeoff and landing distances (STOL). The set of technical solutions considered in the work for reducing takeoff and landing distances for regional aircraft includes:

- aerodynamic design of a high-lift wing,
- analysis of the effect of spoilers on wing lift control during landing approach,
- analysis of the effect of spoilers on the aerodynamic performance of an airplane model during a run,
- evaluation of the effectiveness of the considered technical solutions for reducing takeoff and landing distances of a regional aircraft ATR 42-600 type.

Aerodynamic design of a high-lift wing

Expanding regional aircraft runway lengths, ensuring their use at a larger number of airfields, is one of the important tasks currently considered in the development of new aircraft configurations. Aerodynamic parameters directly affecting the flight range and runway lengths are cruising aerodynamic quality and available values of maximum wing lift coefficients in takeoff and landing configurations. With the selected wing geometry, the free parameters that affect the cruising quality and lifting properties of the wing are the geometric parameters of the wing airfoils (sections) and high lift devices. According to the significance of influence, these parameters are the second most important factor after the choice of the wing planform.

The paper presents the aerodynamic design of the wing high lift devices of a regional propeller-driven aircraft with the value level $Cy_{max} \approx 3.3$, including:

- the use of a new A18 root profile (c = 18%) with an increased level of lifting properties and satisfactory values of drag and pitching moment in cruise flight,

[3] ATR 42-600. atr-aircraft.com. Available at: https://www.atr-aircraft.com/aircraft-services/aircraft-family/atr-42-600/ (accessed: 07.12.2023).

[4] Appendix 4 to Opinion No 02/2019. EASA. Available at:https://www.easa.europa.eu/en/downloads/71568/en (accessed: 07.12.2023).

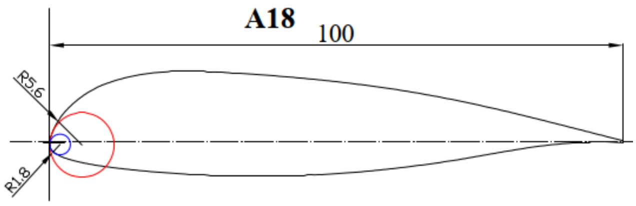

Fig. 4. Geometry of A18 root airfoil

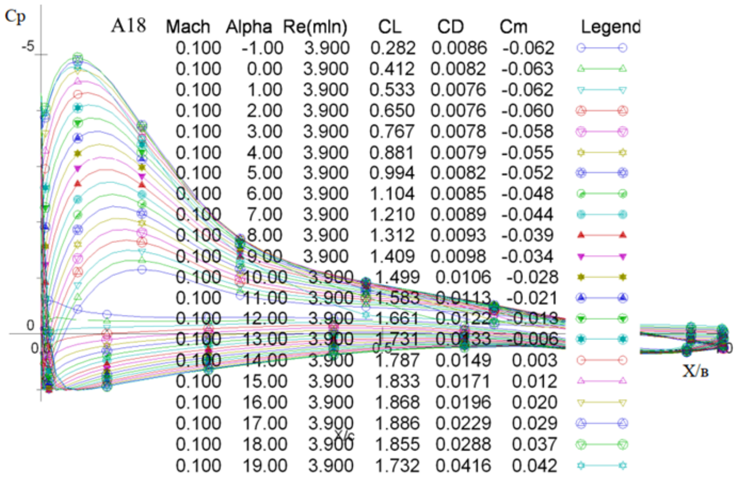

Fig. 5. Design characteristics of the A18 airfoil determined by the VISTRAN program [12]

- design of adaptive trailing edge high lift devices,
- design of a simplified version of the wing leading edge high lift devices, including a slotted Krueger.

To meet the complex requirement for high lifting properties of the wing, the previously developed A18 root airfoil was used [10]. Figure 4 shows the geometry of the A18 airfoil, which is characterized by a thickened rounded nose with an increased radius of mating with the contour of the upper surface of the airfoil and a small radius of mating with the contour of the lower surface. The front positions along the profile chord of maximum concavity and thickness are supplemented by a small "cut" of the lower surface at the end of the profile, reducing balancing losses.

The noted features of the root airfoil geometry provide a rounded (peak-free) pressure distribution shape in the nose section at elevated angles of attack, which, in combination with the remaining declared profile parameters determined using the PARSEC method [11], contributes to the attached flow around the upper surface up to the values of the coefficient Cy (CL ≈ 1.2). The subsequent smooth development of separation with an increase in the angle of attack ensures the achievement of high values of the coefficient *Cy* at low flight speeds (Cy_{max} ≈ 1.9; fig. 5).

With a moderate value of the pitching moment Cm ($|m_z|$ = 0.063; α = 0), the A18 airfoil has an advantage in the value of the Cy_{max} coefficient equal to 8% and 14.5%, compared to the well-known root profiles MS(1)-0318 and NACA 43018 (fig. 6), installed in the wing configurations of a number of regional aircraft.

The first of the specified profiles was used in the root sections of the wing configurations of the regional aircraft Saab 340, Saab 2000 and Let L-610, a modification of the second is installed in the wings of the ATR 42 and ATR 72 aircraft.

The speed characteristics of the A18 profile (C_x = f(M); fig. 7) correspond to the shock-free pressure distribution on the upper surface up to

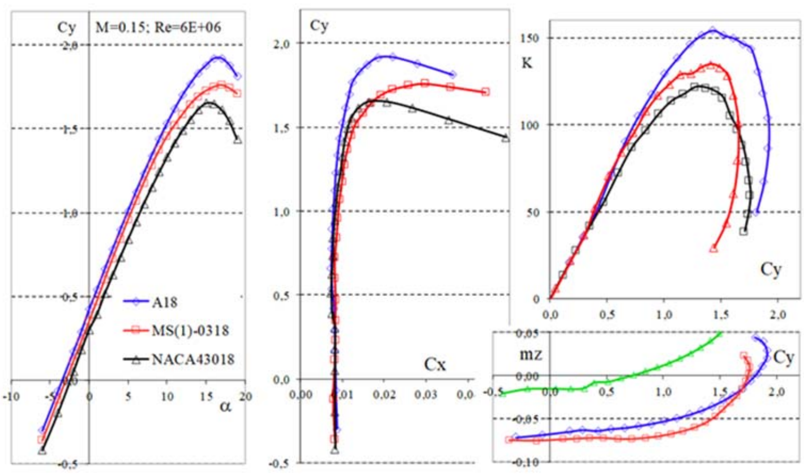

Fig. 6. Comparison of wing root airfoils characteristics

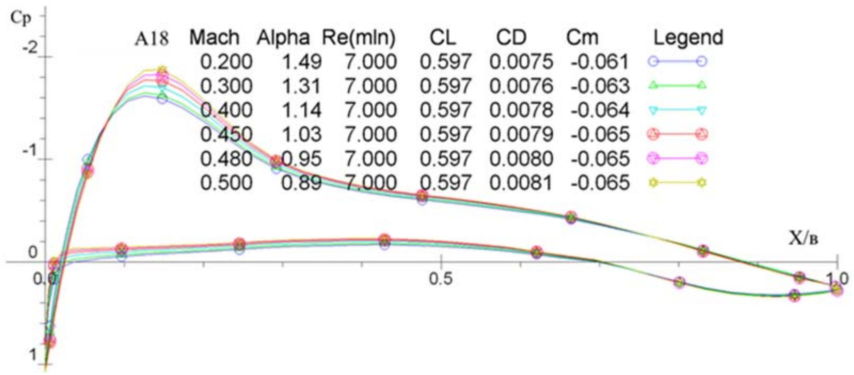

Fig. 7. Effect of Mach number on airfoil drag

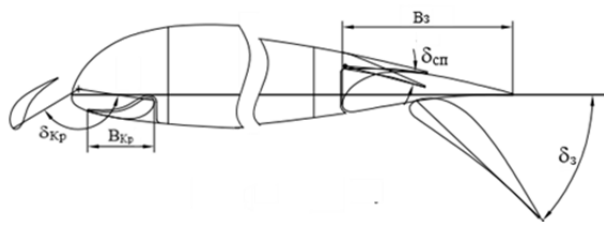

Fig. 8. High-lift system of the wing root section

the Mach number M ≈ 0.5 (C_y ≈ 0.7). This value of the Mach number corresponds to the maximum cruising speed $V_{cr.max}$ = 556 km/h of the ATR 42-600 aircraft, realized with the calculated value Cy_w ≈ 0.45 (H = 7.2 km).

To increase the wing lift and reduce the takeoff and landing distances of a regional aircraft, an effective leading and trailing edges control surfaces have been developed (fig. 8), including an adaptive version of the Fowler flap and a slotted Kruger.

Adaptation of the high lift devices in takeoff and landing flight modes is achieved by integrating the extension of a single-slotted flap with a downward turn of the spoiler at small angles. The results of a large cycle of studies of the adaptive flap variant in the TsAGI wind tunnel, published in work [13], showed its increased efficiency, equivalent to

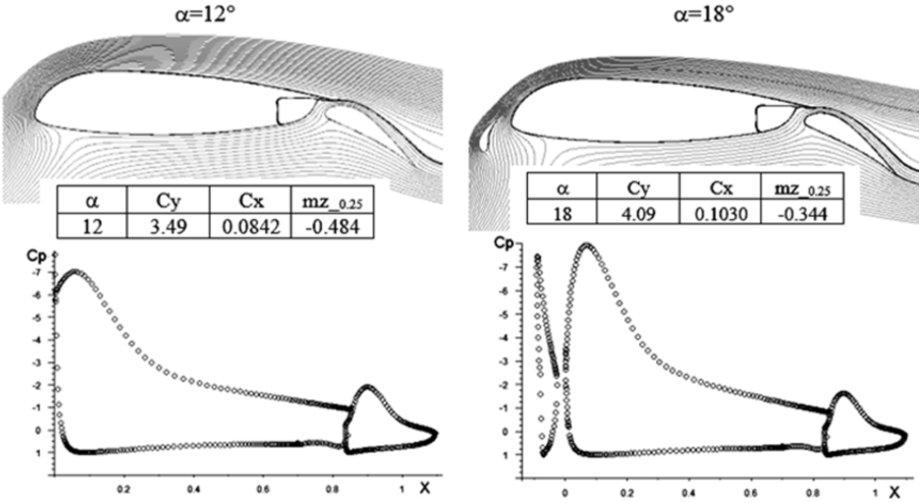

Fig. 9. Effect of the Kruger flap on the wing root section aerodynamic performance ($\delta_f = 35°$; $M = 0.11$; $Re = 3.9 \cdot 10^{P}$)

an increase in the number of links of a conventional flap by one link. The downward deflection of the spoiler provides both a preliminary turn of the flow in front of the flap and adjustment of the gap size between the trailing edge of the main part of the wing and the flap tip for all operating positions, including small deflection angles. Variation of the gap size in the landing configuration can also be used to control the wing lift and the approach angle without changing the aircraft attitude.

The adaptive version of the trailing edge control surfaces, including the integration of spoilers deflected downwards at small angles with the flap rotation function, is used in the wing configurations of the new long-haul aircraft (LHA) Boeing B 787 [14] and Airbus A350XWB [15]. Both aircraft are based at airports with a runway length of more than 2700 m. The significant reduction in the complexity and weight of the trailing edge control surfaces achieved in this case leads to deterioration of the lifting properties of the wing in takeoff and landing modes compared to the classic version of the trailing edge control surfaces, including a retractable Fowler flap.

The use of only the adaptive version of the flap with a high increment of lift in the linear section is clearly insufficient to achieve the target value of the wing Cy_{max} coefficient of 3.3 in the landing configuration; leading edge controls are necessary. The retractable slats currently used in swept wing configurations have complex extension kinematics (along curved guides) and are far from optimal in terms of lifting properties and drag. The small curvature of the centerline and the presence of a sharp protrusion ("vortex generator") on the lower surface make it difficult to obtain high Cy_{max} values of the wing in the landing configuration. Giving the slat a streamlined shape as a result of its location in a well on the lower surface of the wing leading edge and using simple extension kinematics by rotating the hinge relative to the fixed position allow it to be considered as an alternative option for wing leading edge controls. The test results of an improved slat with a chord of ≈12.7% presented in work [16] showed its significant advantage in aerodynamic performance of the wing model compared to the retractable slat with a chord of 15 %. In this paper, instead of the previously used name "improved slat", the more well-known and frequently used name – slotted Krueger – is adopted.

Calculations of the two-dimensional flow around a power-driven airfoil in a landing configuration with deflected leading and trailing edge control surfaces were carried out within the framework of the Reynolds-averaged Navier-Stokes equations. The use of a slotted Krueger with increased lifting properties made it possible to reduce the effective angle of attack of the main airfoil due to the flow slope behind the flap and to ensure a favorable flow pattern around the high-lift system to greater values of the angle of attack compared to the previously considered similar configuration without a flap (fig. 9).

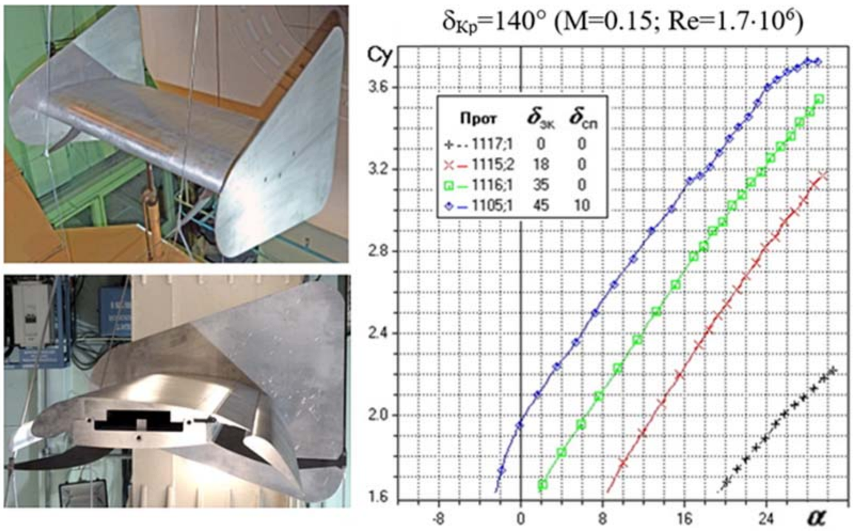

Fig. 10. Wind tunnel tests results of the wing section with a new root airfoil and effective high-lift system

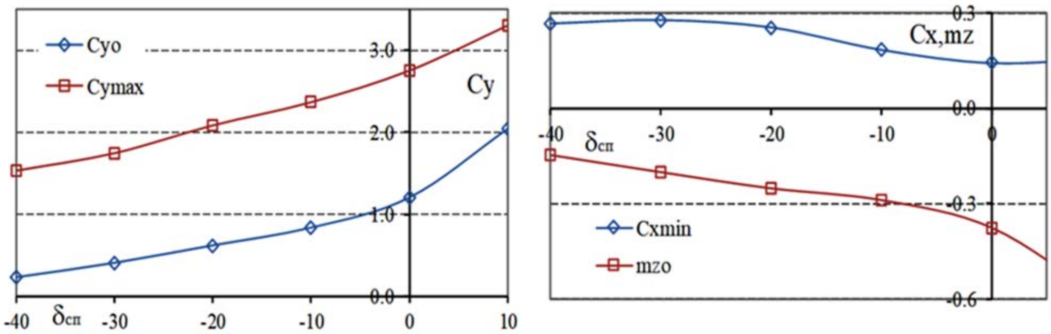

Fig. 11. Effect of the spoiler deflection angle on the model aerodynamic performance with adaptive flap ($\delta_f = 45°$)

The results of the root profile tests with adaptive trailing edge controls and the Krueger flap, conducted in the T-102 wind tunnel in the wing section configuration, showed increases in the critical angle of attack $\Delta\alpha_w \approx 5.5°$ and the Cy_{max} coefficient ($\Delta Cy_{max} \approx 0.42$) from the use of the flap. The maximum value Cy_{max} of the model in the landing configuration was 3.73 (fig. 10).

The upward deflection of the spoiler reduces the concavity of the main part of the wing and increases the size of the gap between the trailing edge of the main profile and the flap nose. This leads to a decrease in the lifting properties of the entire high-lift system both in the linear section and in the area of critical angles of attack (fig. 11). The lifting properties of the model in the landing configuration with a spoiler deflection angle of −30° ($Cy_{max} \approx 1.6$) are close to similar values of the model with the original profile. A decrease in the lifting properties of the wing also contributes to the creation of an increment in the pitching moment for pitching up and an increase in drag.

Estimation of takeoff and landing distances of the ATR 42-600 type aircraft with a high-lift wing

The assessment of the lifting properties of the ATR 42-600 aircraft wing, carried out on the basis of the results of calculated and experimental studies of the high-lift wing, showed the following level of increments of the wing in takeoff and landing configurations:

- $\Delta Cy_{max\_TO} = 0.94$ ($\delta_f = 18°$; $\delta_{f.\,Kr} = 150°$),
- $\Delta Cy_{max\_L} = 1.79$ ($\delta_f = 45°$; $\delta_{f.\,Kr} = 140°$).

Table 3

Comparison of the performance of an ATR 42-600 aircraft type
with the original and high-lift wings

	Initial wing configuration		**Improved wing profile and high lift devices**	
	Takeoff	Landing	Takeoff	Landing
Cy_{max}	1.99	2.47	2.74	3.32
Vs, m/c	52.3	46.6	40.1	35.5
$Cy_{l.a.}$		1.63		2.19
$V_{l.a.}$, km/h		206.5		157
Distance, m	1177	984.5	860	810
Runway length, m	1354	1408	989	1158

The predicted level of values of the coefficient Cy_{max} of the wing with a modified profile and high lift devices, obtained according to the previously described method, can be:

- $Cy_{max} =$ 1.79 – cruising configuration,
- $Cy_{max} =$ 2.74 – takeoff configuration,
- $Cy_{max} =$ 3.32 – landing configuration

The increase in the Cy_{max} values of the wing in takeoff (ΔCy_{max} = 40.5 %) and landing (39.4 %) modes, obtained as a result of using the new wing profile and high lift devices, made it possible to significantly reduce the calculated values of the aircraft takeoff and landing distances and the required runway lengths (tab. 3), determined with regard to the safety factors of 1.15 (takeoff) and 1.43 (landing) for the declared takeoff and landing values of the aircraft weight, equal to 18,600 kg and 18,300 kg, respectively (see Table 1).

The noticeable differences in the takeoff and landing distances and required runway lengths of the ATR 42-600 aircraft, obtained with the same mass and thrust values of the aircraft characteristics, are due to the differences in the lifting properties of the two wing variants (Cy_{max}).

In accordance with the methodology used to evaluate the takeoff and landing distances of the aircraft, the resulting reduction in the takeoff distance corresponds to the level of the Cy_{max} increment of the wing, while for the landing distance, where the Cy_{max} value affects only the length of the landing section, the reduction was only 16.6%. However, a significant increase in the lift coefficient value during the landing approach ($Cy_{l.a.} = Cy_{max} / 1.23^2$), as well as the expected increase in drag in the landing configuration, can be used for a steep approach for landing in order to reduce the length of the air leg and the negative impact of noise on neighboring residential areas of the local airport.

A comparison of the landing approach speed of the ATR 42-600 aircraft with the developed high-lift wing with the landing approach speed values ($V_{l.a.}$) of known civil and military aircraft given in work [6] is shown in Figure 12.

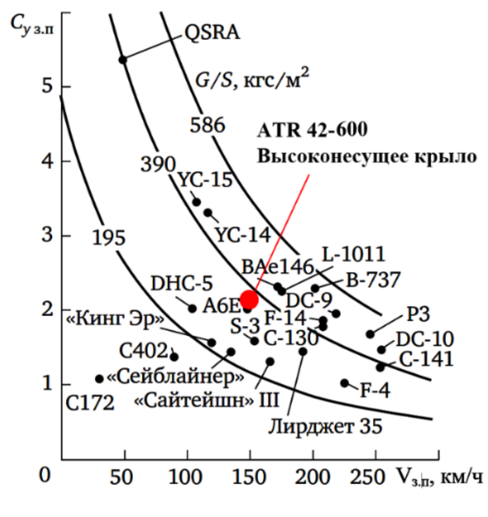

Fig. 12. Approach speeds for civil and military aircraft

The dependence of the landing approach angle (θ) on the ratio of drag *(X)* to lift *(Y),* as well as on engine thrust *(T)* and aircraft weight *(G)*, given for the condition V = const,

$$\sin(\theta) = \frac{X}{Y} - \frac{T}{G} = \frac{1}{K} - \frac{T}{G}. \quad (5)$$

Fig. 13. Photo of the ATR 42-600S (STOL) aircraft

makes it possible to use the increase in aircraft drag with deflected high lift devices and engine thrust control for a steep approach.

To control an aircraft when flying along a steep glide path, a direct lift control system (DLCS) is also required, with the help of which it is possible to change the descent rate without changing the aircraft orientation in space. At the same time, to ensure good visibility and eliminate the leveling mode during landing, the wing must have high values of the lift coefficient at small pitch angles [6].

The devices that allow the wing lift to be controlled during landing include high-speed flaps and multifunctional spoilers used in conjunction with the aircraft longitudinal controls. A previous study of the effectiveness of external spoilers on a light transport aircraft model in a landing configuration showed that their deflection by an angle of $\delta_{af} = -25°$ leads to a decrease in aerodynamic quality and Cy_{max} by an average of 11%. A greater effect can be achieved by deflecting internal spoilers.

Evaluation of takeoff and landing distances of the ATR 42-600S aircraft type with the original wing aerodynamics

In 2020 the regional aircraft manufacturer ATR announced its intention to launch a new version of the ATR 42-600S aircraft (fig. 13), capable of taking off and landing on a runway with a length of 800 m[5]. The introduction of a new version of the STOL aircraft should expand its capabilities for operation at a larger number of airfields with a runway length not exceeding 1000 m. Thus, ATR intends to enter the market of 19-seater aircraft with a projected demand of more than 500 aircraft.

Providing short takeoff and landing distances is expected to be achieved by implementing a number of modifications to the basic model of the ATR 42-600 aircraft, including:

- replacement of the original Pratt & Whitney Canada PW127 engines (2400 hp) with a more powerful PW120XT-L series (2750 hp) with greater takeoff thrust,
- a new braking system with automatic extension of spoilers during takeoff,
- increased flap deflection angle during takeoff from 15° to 25°,
- increased area of the vertical tail and rudder to counteract the yaw moment in the event of engine failure,
- rudder deflection to counteract the yaw moment in the event of engine failure.

In accordance with the concept adopted by the developer, the STOL mode also assumes a reduction in the maximum takeoff weight of the aircraft from Go = 18,600 kg to 16,032 kg as a result of reductions in payload (coefficient 0.7) and flight range to 200 NM (370.4 km). The landing weight of the aircraft, taking into account 5% of the remaining fuel from the takeoff value of 577 kg, is estimated at 15,484 kg.

The expected takeoff and landing performance of the modified ATR 42-600S aircraft,

[5] ATR 42-600S. atr-aircraft.com. Available at: https://www.atr-aircraft.com/wpcontent/uploads/2022/06/ATR_Fiche42-600S-3.pdf (accessed: 07.12.2023).

Table 4

Take-off and landing performance of the modified ATR 42-600S aircraft

Pratt & Whitney Canada engines	PW127XT-L
Takeoff power, hp	2 × 2750
Weights	
Maximum takeoff weight (MTOW), kg	18600
Maximum landing weight (MLW), kg	18300
Maximum weight without fuel, kg	17000
Empty weight, kg	11850
Maximum payload weight (PL), kg	5150
Maximum fuel weight, kg	4500
Aerodrome characteristics	
Takeoff distance, m (under the following conditions):	
- Takeoff weight for a flight of 370.4 km (70% PL, ISA, SL)	800
- Takeoff weight for a flight of 555.6 km (PL_{max}, ISA+10, SL)	920
Landing distance, m (under the following condition):	
Takeoff weight for a flight of 370.4 km (70% PL, ISA, SL)	810
Standard flight range, km	370.4
Fuel weight, kg	577

taken from the official data of the developer, are given in Table 4.

With the specified aerodynamics of the ATR 42-600S aircraft for the takeoff flap position ($\delta_f = 25°$, $Cy_{max} \approx 2.24$) and adjusted weight characteristics, the following calculated values of takeoff and landing distances and required runway lengths were obtained:

- takeoff – $L_{T.D}$ = 683 m (L_{RWY} = 1.15, L_{LD} = 786 m),
- landing – L_{LD} = 707 m (L_{RWY} = 1.43, L_{LD} = 1011 m).

When calculating the landing distance, the average statistical reduction in the takeoff distance was taken into account when using the braking system with the spoilers extension on the roll[6], which allows reducing the run section by ≈30 % ($\Delta L_{run} = -173$ m).

An additional reduction in the landing distance and required runway length is possible when landing on a steep glide path with an approach angle exceeding the fixed value of 3° for Instrument Landing Systems. Currently, an increased approach angle is used at a number of airports, for example, at London City Airport [9].

The increase of the approach angle for the ATR 42-600S aircraft from 3° to 5.5° additionally reduces the air leg length by $\Delta L_{as} = -131$ m and the landing distance to 576 m, providing a calculated value of the required runway length of 824 m, close to the declared value of 810 m (tab. 4).

Evaluation of takeoff and landing distances of the ATR 42-600 aircraft type with improved wing aerodynamics

A similar assessment of takeoff and landing distances was carried out for the ATR 42-600 aircraft using the calculated values of the Cy_{max} coefficient of the wing with modified profiling and high lift devices in takeoff and landing modes. Increasing the wing lifting properties to the values of Cy_{max} = 2.74 – takeoff configuration and Cy_{max} = 3.32 – landing configuration allows, while maintaining the initial weight data of the aircraft, to ensure the following estimated takeoff and landing characteristics:

6 FSF ALAR Briefing Note 8.3. Landing Distances. flightsafety.org. Available at: https://flightsafety.org/files/alar_bn8-3-distances.pdf (accessed: 07.12.2023).

- takeoff – $L_{T.D}$ = 750 m (L_{RWY} = 1.15, L_{LD} = 862 m),
- landing – L_{LD} = 811 m (L_{RWY} = 1.43, L_{LD} = 1159 m).

The use of spoilers on the landing roll ($\Delta L_{run} = -173$ m) and steep approach for landing θ = 5.5° ($\Delta L_{as} = -131$ m) significantly reduces the landing distance and the required runway length to the values of L_{LD} = 528 m and L_{RWY} = 1.43, L_{LD} = 755 m.

To meet the runway length requirement at takeoff, an increase in the lifting properties of the wing in the takeoff configuration was considered by increasing the flaps angle from 18° to 25°. Most high-lift devices of the trailing edge of regional aircraft have the ability to select several discrete high-lift device deflection angles during takeoff, depending on the takeoff weight and the available runway length. An increase in the flap angle leads to an increase in the Cy_{max} values of the wing, a decrease in the stall speed Vs and, accordingly, the takeoff roll length. However, the accompanying increase in drag and decrease in aerodynamic quality can lead to an increase in the length of the air leg. It can also be difficult to meet the airworthiness standards for the climb gradient value on the second leg, especially with a failed engine.

$$\sin\theta = T/G - X/Y .$$

A rational choice of the takeoff configuration of the high-lift devices depends on the takeoff weight and consists in finding the optimal compromise between maximum lift and aerodynamic quality.

The expected Cy_{max} value of a high-lift wing from changing the flap angle from 18° to 25°, determined on the basis of the calculated Cy_{max} values for takeoff and landing configurations, may be 2.91. This allows us to come significantly closer to meeting the runway length requirement (L_{as} = 706 m; L_{RWY} = 1.15 L_{LD} = 811 m)

A similar effect on reducing the takeoff distance can also be achieved by reducing the initial takeoff weight of the aircraft from 18,600 kg to 17,251 kg by reducing the payload weight by 26% or the flight range. In this case, the calculated values of the aircraft takeoff performance, while maintaining the flap angle of 18°, will meet the basing requirement of an ATR 42-600S aircraft on a runway no longer than 800 m, achieved with a smaller reduction in payload and a greater flight range, relative to the ATR 42-600 aircraft (L_{as} = 696 m; L_{RWY} = 1.15 L_{LD} = 800 m).

Of the two considered options for reducing the takeoff distance of an ATR 42-600 aircraft, the option with an increase in the lifting properties of the wing by ΔCy_{max} = 0.172 or by 6.3% relative to the initial value Cy_{max} = 2.74 is more preferable. The latter can be achieved by optimizing the geometric parameters and positions of the considered wing high lift devices with a minimum increment of profile drag.

Conclusion

Two approaches were considered to reduce takeoff and landing distances of regional aircraft.

The first, proposed by the Franco-Italian consortium, included replacing the original ATR 42-600 engines with more powerful PW120XT-L series (2 × 2750 hp), increasing the flap angle during takeoff to 25°. A new braking system was also developed and the takeoff weight was reduced to 16,032 kg by reducing the payload and the flight range to 370.4 km.

The proposed modifications of the ATR 42-600 aircraft made it possible to reduce the takeoff distance to L_{as} = 683 m (L_{RWY} = 786 m), however, in the landing configuration, an additional increase in the approach angle from 3° to 5.5° is required, which makes it possible to reduce the landing distance from 707 m to 576 m (L_{RWY} = 824 m).

In the second approach, the main attention was focused on increasing the wing lift. The development of new wing airfoil with an increased lifting properties, as well as the design of effective high lift devices, made it possible to significantly increase the level of the Cy_{max} coefficient values of the regional aircraft wing to the following values:

- cruise configuration – Cy_{max} = 1.79,
- takeoff configuration – Cy_{max} = 2.74,
- landing configuration – Cy_{max} = 3.32,

which significantly exceed similar Cy_{max} values of the ATR 42-600 aircraft wing with a double-slotted rotary flap: 1.57, 2.0 (δ_f = 15°) and 2.47 (δ_f = 35°).

The achieved level of lift values, as well as the use of spoilers during takeoff roll and a steep landing approach (θ = 5.5°), provide a reduction in the landing distance of the ATR 42-600 aircraft to L_{LD} = 528 m (L_{RWY} = 755 m). It is impossible to meet the requirement for the runway length during takeoff with the initial engine power (2 × 2400 hp) (L_{as} = 808 m; L_{RWY} = 930 m). The considered increase in engine power to N = 2 × 2750 = 5500 hp (ATR 42-600S aircraft), as well as increase of the flap angle to 25° (ΔCy_{max} = 0.172) made it possible to come closer to meeting the runway length requirement (L_{as} = 706 m; L_{RWY} = 811 m) while maintaining the original data of the ATR 42-600 aircraft.

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