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CONCEPTUAL DESIGN OF NEW HEAVY TRANSPORT AIRCRAFT

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This paper presents the conceptual design study results of the heavy transport aircraft, which is proposed for replacement of An-124 aircraft in the airfreight niche. Major parameters of aircraft layout were chosen. Preliminary aerodynamic characteristics and weights of chosen layouts are defined. Wing aerodynamic design was performed. Aircraft performance was calculated. Selected geometric and weight parameters guarantee transportation of 150 t payload with cruise speed 850 km/h at 7000 km range with required airfield length 3000 m. With maximum payload 180 t practical range is about 4900 km. Takeoff weight limits for operations from airfield with 2500 m are determined.

1. Introduction

Antonov An-124 cargo aircraft are an indispensable means for transporting various large-size cargo, as evidenced by the experience of the Russian Aerospace Forces military operations and many civilian operations with non-standard cargo.
Intensive usage of An-124 aicraft will lead to the end of the airframe life (even with its prolongation), what leads to the end of aircraft operation. Attempts to resume the production of An-124 aircraft were failed. Taking into account technical and moral obsolescence (aerodynamics, design, materials and production technologies at level of late 1970s; cargo dimensions growth; relatively high fuel consumption), restoring of its production becomes impractical. The dimensions of the An-124 cargo compartment do not allow to realize the maximum payload when it is completely filled with standard containers. At the same time, the An-124 is capable of transporting a wide range of large-size cargoes, including single cargo with 100 tons weight, which is its main competitive advantage in comparison with freighters.
Thus, there are prerequisites for the development of a new aircraft – "a modern version of the An-124", with improved performance, advanced technology and the latest achievements of aerodynamics, design, materials, control systems [1, 2, 3].
The perspective heavy transport aircraft named "Elephant" (HTA "Elephant", fig.1) should be an adequate replacement of the An-124 for Russia Aerospace Forces and at the same time be attractive for civilian cargo airlines - have a cost-effective transportation of general cargo, comparable to the cargo variants of passenger aircraft.
Based on this background, the following top level requirements were defined:

- Transportation of 150 t payload at 7000 km range, maximum payload – 180 t;
- Cruise speed 850-870 km/h (Mach number 0.8-0.82), flight altitude 9-12 km;
- Takeoff distance 2500-3000 m;
- Ability of loading all cargoes of An-124, outsized cargoes and single cargo with weight up to 150 t;
- Two-ramp loading (forward and aft ramps);
- Removable second deck of the cargo compartment with adjustable height for full utilization of the cargo compartment volume when loading containers and pallets;
- Built-in devices for mechanization of loading/unloading operations of containers and pallets;
- Built-in removable cranes with maximum load capacity 30 t;
- General cargo (full load) loading time – 1-2 hours;
- Single cargo with weight 150 t loading time – 4-6 hours;
- Implementation of modern avionics and aircraft systems;

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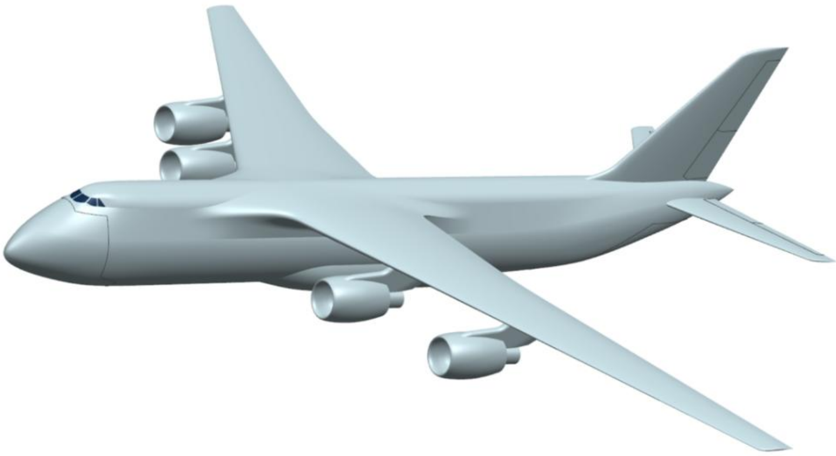

Figure 1: HTA “Elephant”

2. Methods and methodology

The basic layout of the HTA “Elephant” was formed using the well-known engineering methods described in [4, 5, 6], and taking into account the characteristics of the An-124-100, An-225 [7] and Boeing 747-8F [8] aircraft.
Parametric studies of aircraft sizing was performed in program for estimation of rational aircraft parameters with usage of TsAGI’s engineering methods. The program is based on the well-known weight balance or unity equation of an aircraft. The solution of this equation is carried out by an iterative method.
The aerodynamic design of the wing airfoils was carried out with tool [1, 9], which includes: a system for aircraft shaping, direct methods for analyzing aerodynamic characteristics, inverse methods for making geometric shapes from a given pressure distribution and optimization methods. The aerodynamic design of wing for the HTA “Elephant” was performed in the BLWF-56 program as a direct method.

3. Concept. Baseline sizing

The conventional aerodynamic configuration (similar to the An-124 aircraft) was accepted for the HTA “Elephant” – a high-placed swept wing scheme with horizontal and vertical stabilizers located on the fuselage. The layout of the aircraft is supposed to apply the following innovations: a wing with high aspect ratio ($\lambda \geq 10$) and increased taper ratio ($\eta \approx 4$) with modern supercritical airfoils, high bypass turbofan engines (PD-35), a removable second cargo deck, modern metal and polymer composite materials, and other promising technologies.
The fuselage layout of the HTA “Elephant” (fig.2) was designed with preservation of the technical solutions used on the An-124 aircraft:

- Two cargo doors with ramps (avoids gas contamination of the cargo compartment when loading vehicles under its own power; allows loading and unloading at the same time);
- Upper deck with cockpit, crew rest cabin and cabin of accompanying personnel.

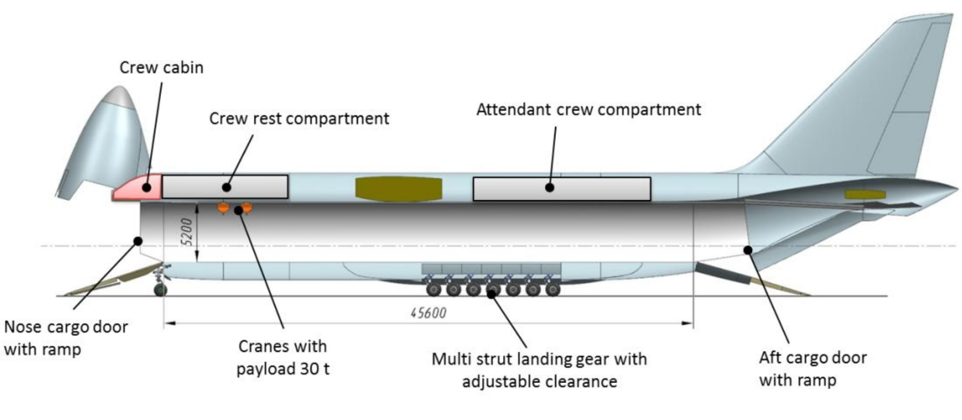

Figure 2: Fuselage layout of HTA “Elephant”

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Based on the transport tasks, 2 variants of the cross-section have been proposed (fig. 3). Sections are formed by the intersection of arcs of circles of different radius.

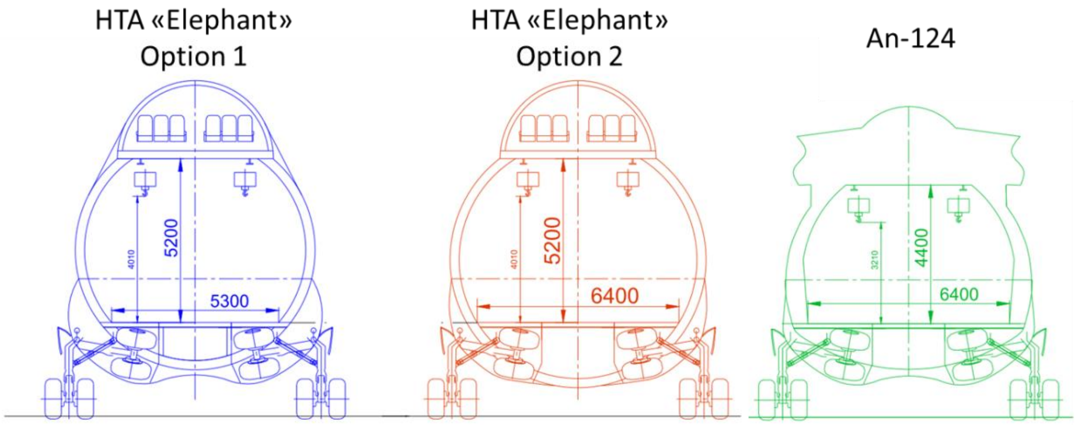

Figure 3: Variants of HTA "Elephant" fuselage cross-section in comparison with An-124

The first variant of the cross-section with a cargo cabin size 5.3 m × 5.2 m (width × height) is optimized for use in cargo airlines using double deck loading of general cargo containers and pallets.
The second variant of the cross-section with a cargo cabin size 6.4 m × 5.2 m allows transporting vehicles (trucks, etc.) in 2 lines similar to the An-124.
The option №1 of the cross section has a smaller area of the mid-section and lower fuselage drag. The advantage of option №2 is the ability to load large vehicles with an overall width of ≥ 2.5 m in 2 lines.
Further parametric studies of the aircraft were carried out on the basis of the selected fuselage size and the specified requirements for payload, range, cruising speed and airfield length.
The figures 4-5 shows the calculation results of the HTA "Elephant" takeoff and landing characteristics depending on the thrust-to-weight ratio and wing loading. These dependences are used in the further calculations for estimation of rational aircraft parameters.

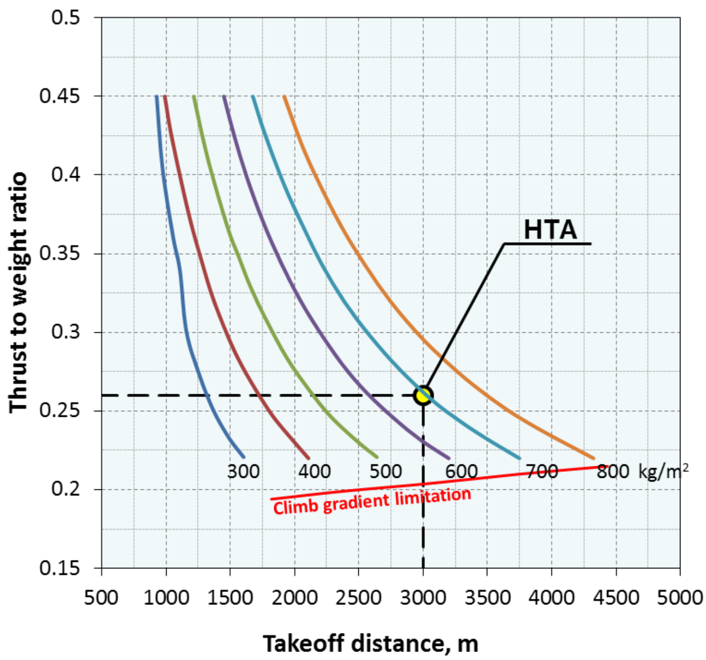

Figure 4: Takeoff performance of HTA "Elephant" (ISA, H=0 m, $C_{L\ MAX}$=2.5)

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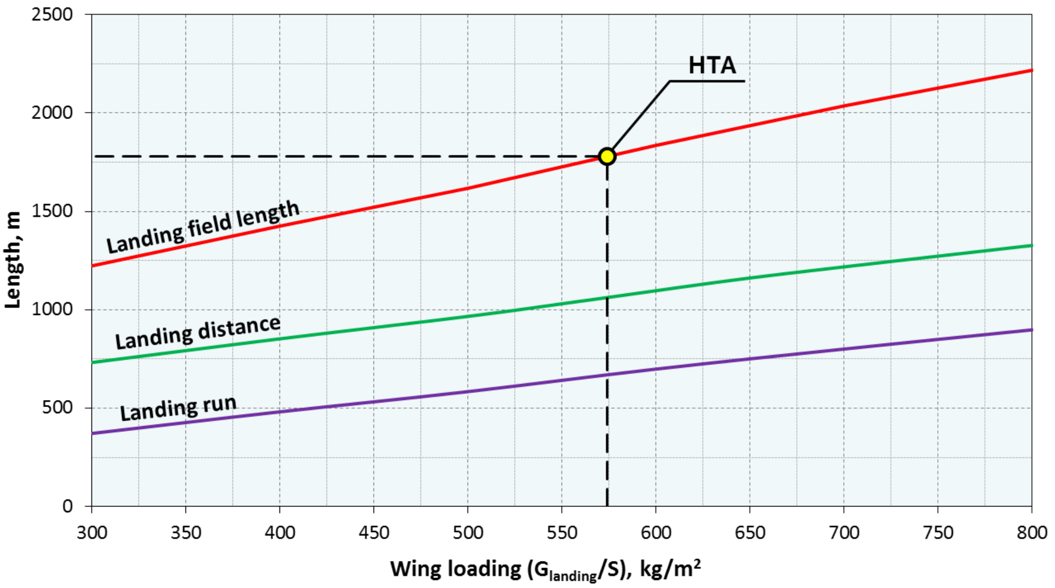

Figure 5: Landing performance of the HTA "Elephant"

The fig. 6 shows the change of HTA "Elephant" (with cross-section №1) depending on the wing loading for a runway length 3000 m. In this case, the optimum wing loading is 690 kg/m^2. The required thrust-to-weight ratio is 0.26, fuel efficiency ≈100 g/(t×km). Estimated maximum takeoff weight (MTOW) is 490.22 t.

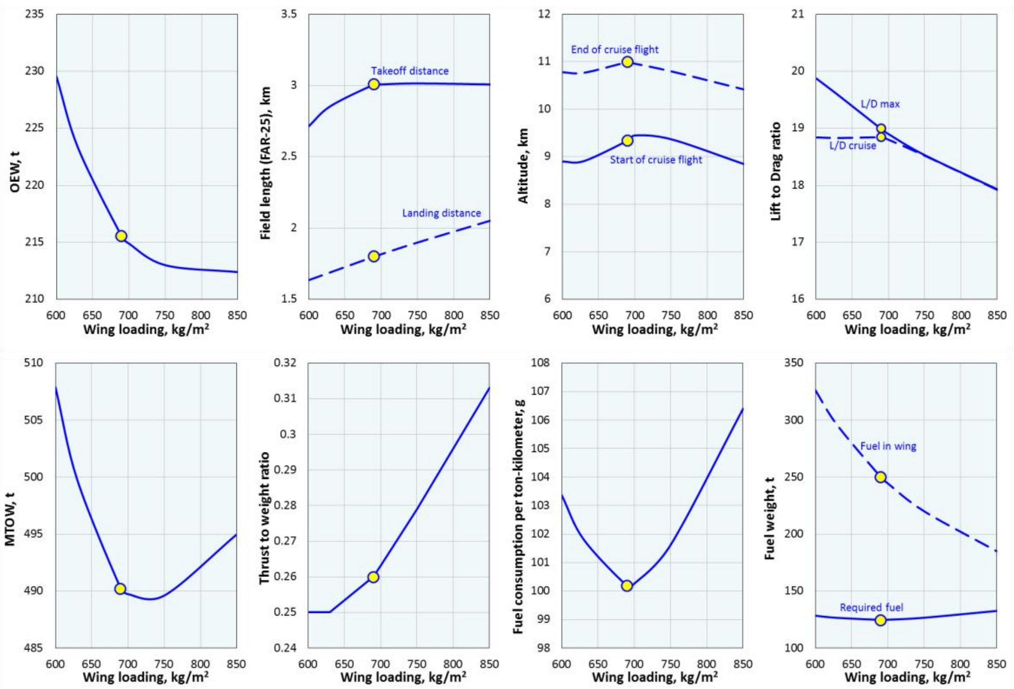

Figure 6: Influence of the wing loading on major aircraft parameters at constant field length 3000 m
(dots indicates the selected variant with wing trapezium area 710.5 m^2)

The aircraft, optimized for runways length 3000 m, has a wingspan of ≈88 m (for example, the wingspan of the An-225 is 88.3 m). Optimization of an aircraft for runway length 2500 m would lead to an increase in wing span of over 90 m and a corresponding increase of MTOW (508 tons) with the same calculated payload (150 t) – the Payload-to-MTOW ratio is worse.
The parameters of the aircraft with runway length 3000 m were taken as a basis. Operations on runways with length 2500 m will perform with lower MTOW through the reduction of payload or fuel weight.
On the basis of the HTA "Elephant" parameters with cross-section №1, the geometric and mass parameters of the aircraft with cross-section №2 are determined with respect to the flight range and airfield length. The HTA

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"Elephant" with cross-section №2 has MTOW 499.14 t, with wing loading 680 kg/m^2. Fuel efficiency is ≈101 g/(t×km).
Weight summary of HTA "Elephant" options are shown in table 1.

Table 1: Weight fractions of HTA "Elephant" variants

	Option №1	**Option №2**
Airframe	150 911	158 665
Powerplant	38 399	38 636
Systems	25 000	25 000
Empty weight	214 310	222 301
Operating empty weight	215 510	223 501
Payload	150 000	150 000
Mission fuel	124 709	125 639
Maximum takeoff weight	490 219	499 140

4. Aerodynamic design of wing

The aerodynamic design of HTA "Elephant" wing was based on the following principles:

- development of modern supercritical airfoils of the basic sections of the wing, providing maximum lift-to-drag ratio in a cruise flight (Mach number 0.8-0.82);
- the use of multi-mode optimization to ensure a moderate level of wave drag over the entire possible cruise flight modes;
- maintaining the required thickness of the wing airfoils to provide internal volumes with the satisfaction of design and operational limitations;
- ensuring wing flow without separation, both in the aircraft cruise flight conditions and in the windtunnel conditions;
- ensuring satisfactory stalling characteristics by protecting wingtip sections from early flow separation;
- flight to the maximum range should be carried out with Mach number 0.8-0.82, (C_L ~ 0.515 - 0.55).

The HTA "Elephant" model for aerodynamics calculations is presented on figure 7.

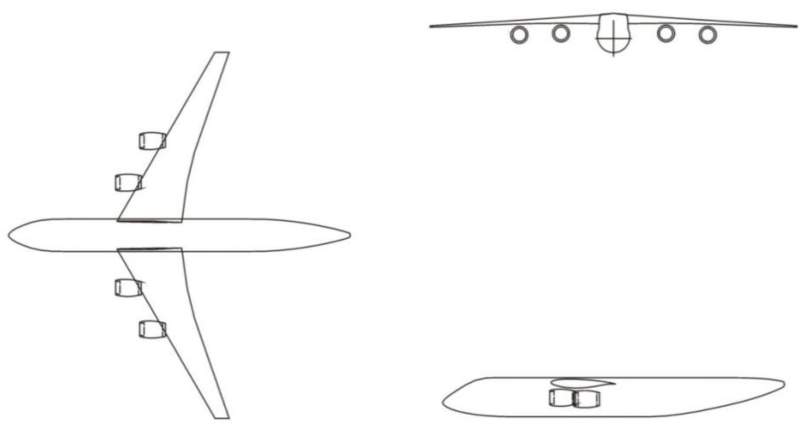

Figure 7: HTA "Elephant" model for BLWF-56 program

The wing (fig. 8) was formed on 6 basic sections in order to take into account influence of the fuselage and engine nacelles and thereby minimize harmful interference.

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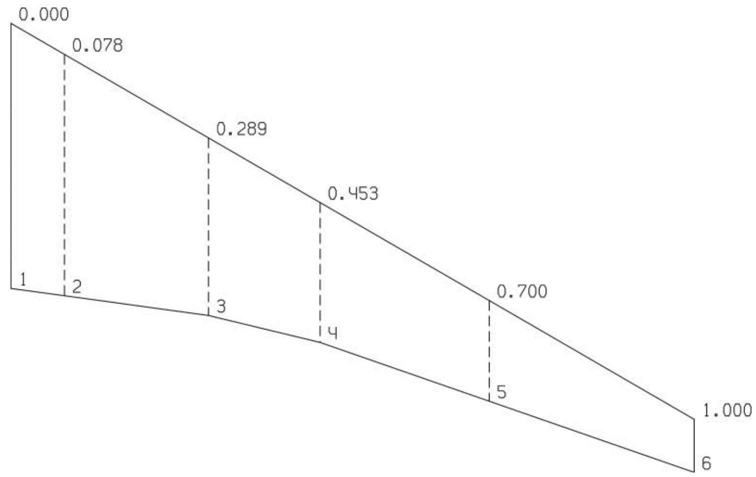

Figure 8: HTA "Elephant" wing planform and its basic sections

The wing shape was designed using a multi-mode optimization algorithm. The wing shape was optimized in the following flight mode: M=0.8 C_L=0.545; M=0.81 C_L=0.535; M=0.82 C_L=0.53; M=0.8 C_L=0.7 (Re=55×10^6), and M=0.82 C_L=0.52 (Re=3×10^6). The last mode was chosen to control the flow around the wing in a windtunnel conditions, and the mode M=0.8 C_L=0.7 to control the buffet boundary.
The figures 9, 10 show the distribution of the relative thickness and flight twist angle along the wingspan of the HTA "Elephant".

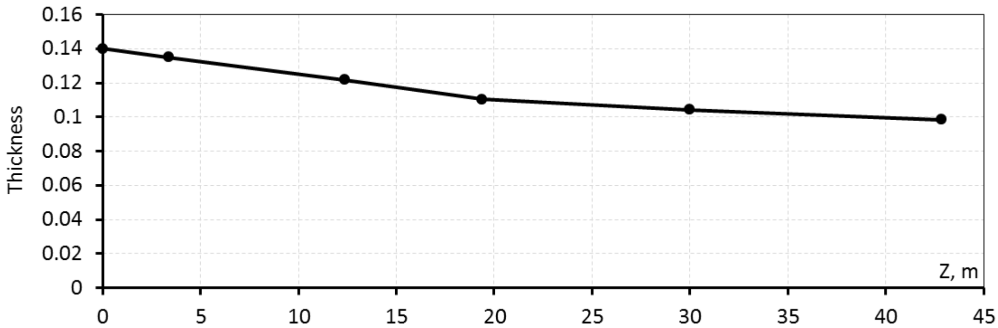

Figure 9: Distribution of the relative thickness along the wingspan

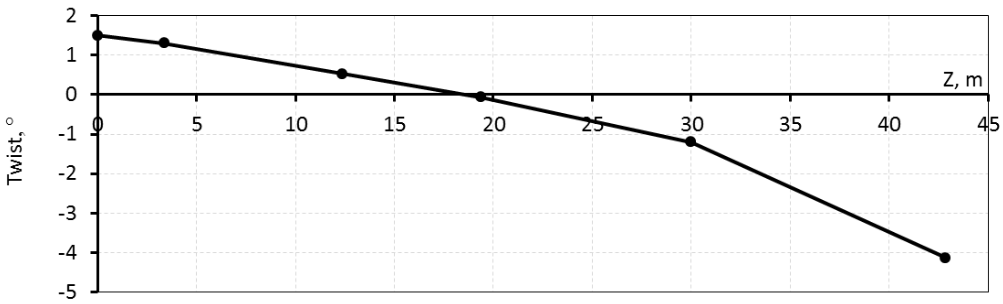

Figure 10: Distribution of the flight twist angle along the wingspan

The figure 11 shows the calculated charts of the form, wave and induced drag coefficient of the HTA "Elephant" depending on the lift coefficient at different Mach numbers M = 0.78; 0.8; 0.81; 0.82 for the natural Reynolds number.
The calculated HTA "Elephant" drag coefficient dependencies on the Mach number for the natural Reynolds number (Re=55×10^6) at lift coefficient C_L=0.5, 0.525, 0.55, 0.575 are presented in the figure 12.

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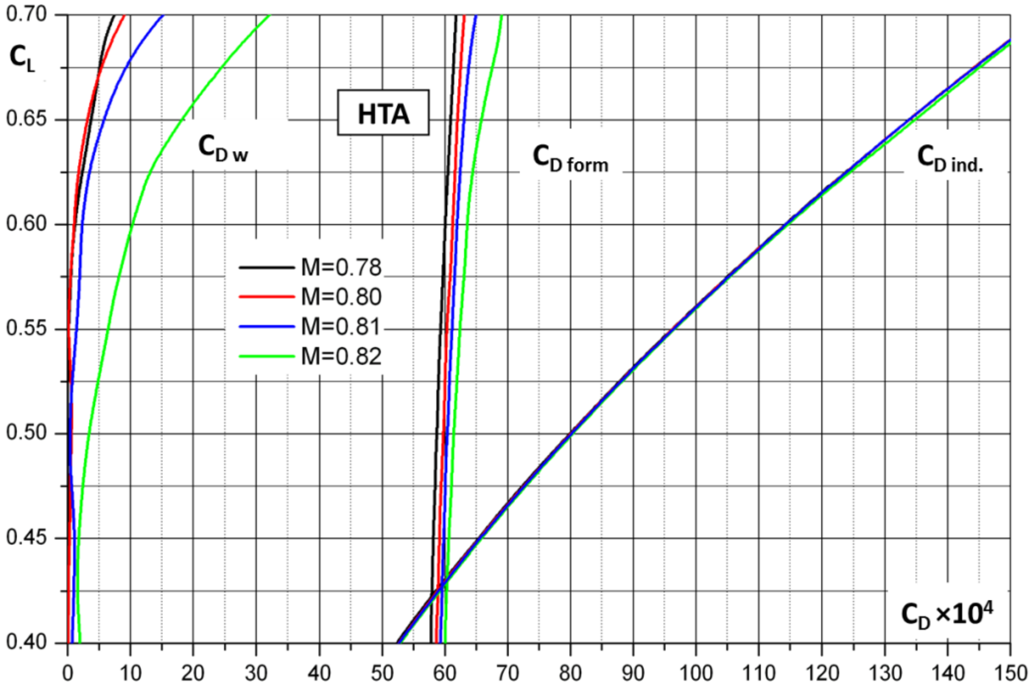

Figure 11: Drag components of the HTA "Elephant" at different Mach numbers and natural Reynolds number ($55{\times}10^6$).

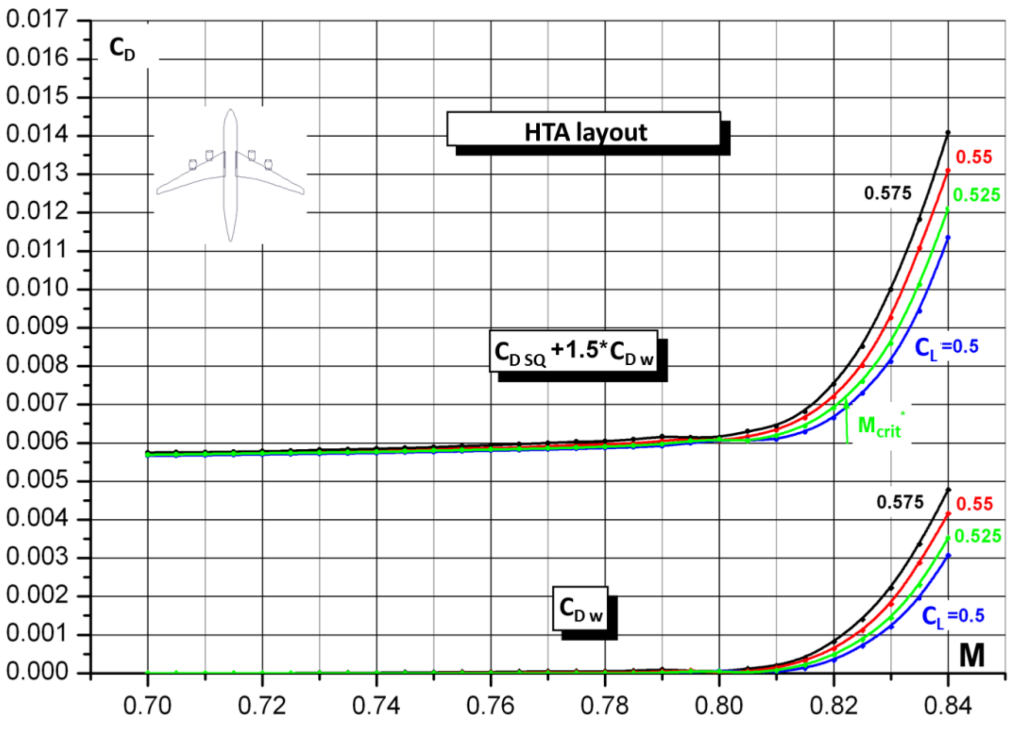

Figure 12: Calculated C_D=f(M) at natural Reynolds number

The presented charts shows that the designed wing in cruising modes M=0.8-0.82; C_L=0.5-0.55 has an insignificant level of wave drag.

The figure 13 represents the estimated L/D ratio for the same Mach numbers M = 0.78; 0.8; 0.81; 0.82 and natural Reynolds number. It should be noted that the $C_{D\ 0}$ value of the HTA "Elephant" was determined on the basis of an experience. The drag components $C_{D\ form}$ (C_L), $C_{D\ wave}$ (C_L), $C_{D\ induced}$ (C_L) were determined using the BLWF-56 program.

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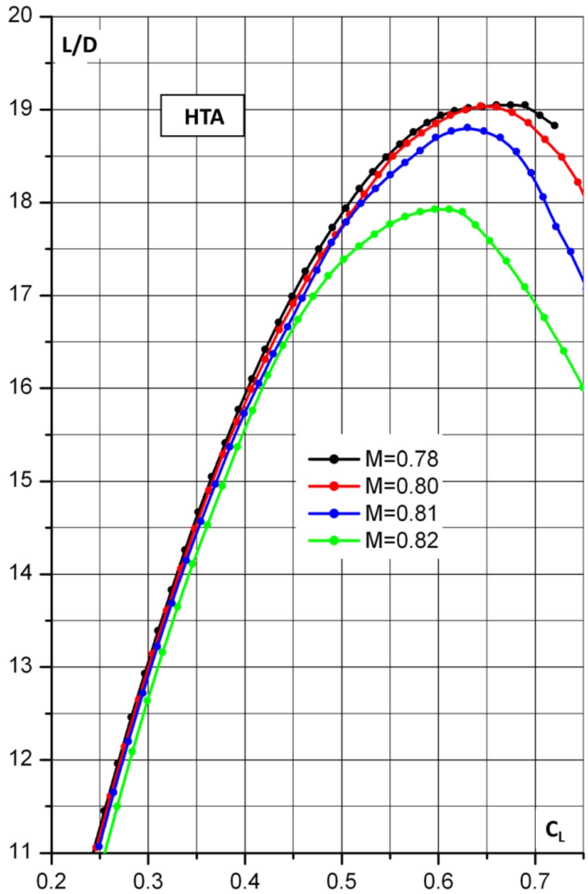

Figure 13: Calculated Lift-to-Drag ratio dependency on lift coefficient at different Mach numbers and natural Reynolds number (55×10^6).

The figure 14 shows the distribution of local Mach numbers on the surfaces of the designed layout.

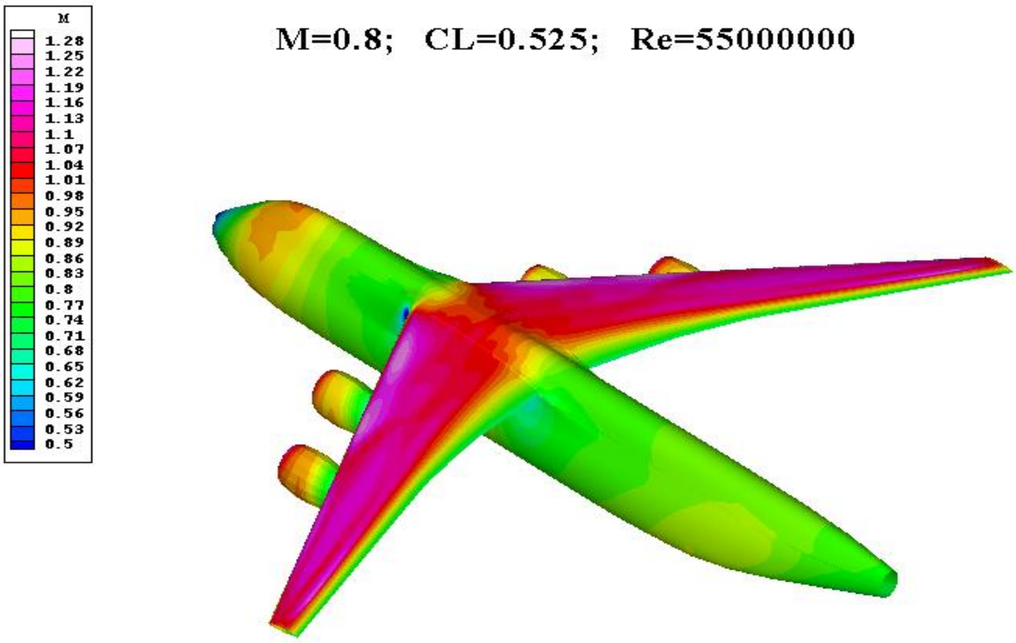

Figure 14: Mach number distribution on the aircraft fuselage and wing

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These studies allow to generate the preliminary aerodynamic configuration of the HTA "Elephant", which will be the basis for creating aerodynamic model for testing wind tunnel TsAGI.
The figure 15 shows the distribution of cross-sectional areas of the HTA "Elephant" along length. The graph also shows a similar relationship for the Sears-Haack body, which has minimal form drag at transonic speeds.

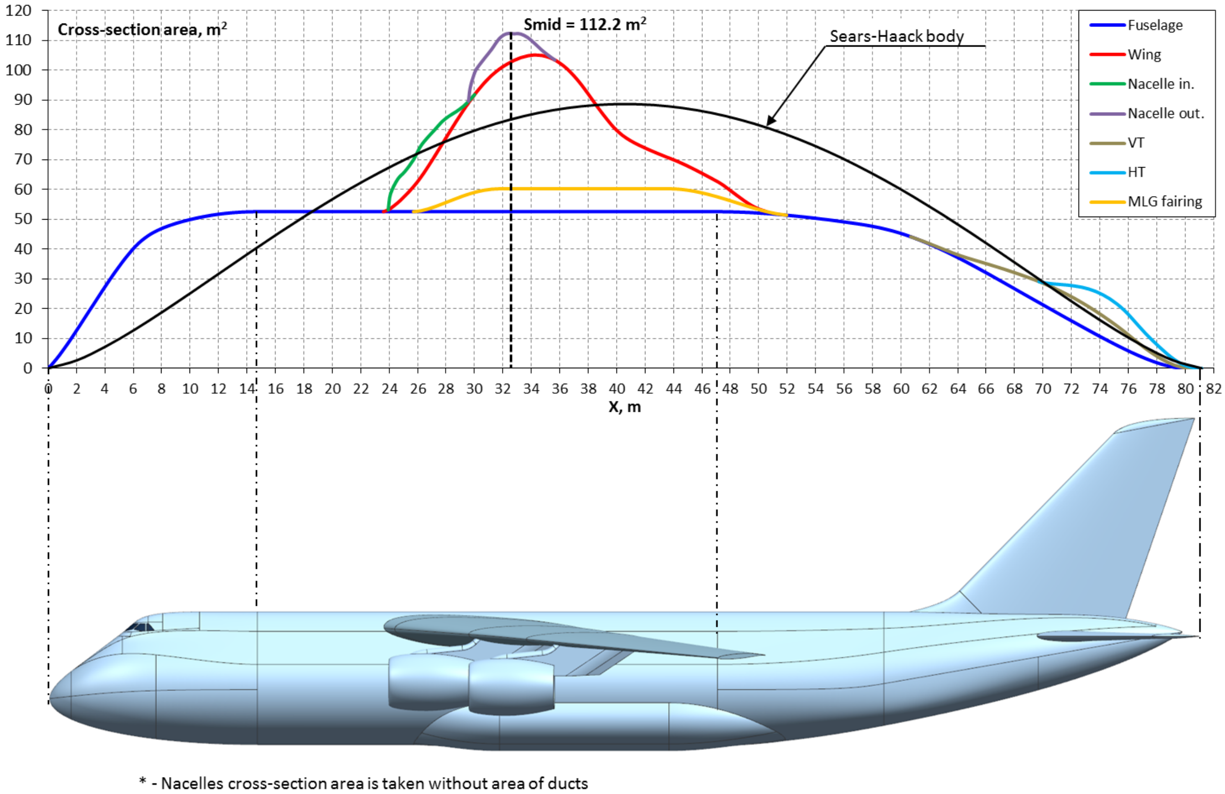

Figure 15: Cross-section area distribution along the length of the HTA "Elephant"

5. Flight performance. Comparison with analogues

Selected geometric and weight parameters provide both variants of the HTA "Elephant" a transportation of 150 t payload with cruise speed 850 km/h (M=0.8) at range 7000 km with required runway length 3000 m. With a maximum payload 180 t practical range is about 4900 km.
The takeoff weight limitations for operations on runway with length 2500 m and reduction of flight range were determined. For variant №1, MTOW is limited to 446 t, while 150 t payload can be transported to 4385 km range, and 180 t - to 2275 km. For variant №2, MTOW is limited to 459.58 t, while 150 t payload can be transported to 4699 km range, and 180 t - to 2600 km.
It is interesting to compare the characteristics of defined aircraft with modern cargo aircraft of similar capacity. The closest analogues of the HTA "Elephant" are the cargo aircraft An-124-100 and Boeing 747-8F. The Airbus A380-800F project [10], which was frozen due to delays in the delivery of the original passenger version and the subsequent cancellation of orders for the cargo version, should be compared too. The main characteristics of the HTA "Elephant" and competitor aircraft are shown in Table 2. Figure 16 shows the "payload-range" diagram of the HTA "Elephant" (variant №1) in comparison with the An-124-100, Boeing 747-8F and Airbus A380-800F.
The use of a removable height-adjustable second cargo deck in the HTA "Elephant" allows the airline to improve the cargo compartment volume filling with respect to the transportation task (fig. 17). At the same time, the possibility of transporting oversized cargo (within the dimensions of the cargo hold) is not available for the Boeing 747-8F and Airbus A380-800F. The transport capability of the HTA "Elephant" in the double deck cargo load option is shown in figure 18.

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Table 2: Comparison of HTA "Elephant" with modern cargo aircraft

	HTA "Elephant" option №1	**HTA "Elephant" option №2**	**An-124-100**	**Boeing 747-8F**	**Airbus A380-800F (project)**
Powerpant	PD-35	PD-35	D-18T series 3	GEnx-2B67	Trent 977
Takeoff thrust, tf	4 x 31.22	4 x 32	4 x 23.43	4 x 30.16	4 x 34.87
MTOW, t	490.22	499.14	392	447.7	590
Max.payload, t	180	180	120	132.6	151.44
Payload/MTOW ratio	0.367	0.361	0.306	0.296	0.257
Thrust/MTOW ratio	0.255	0.256	0.239	0.269	0.237
Wing loading, kg/m^2	641	632	624	789	697
Range, km:					
- with payload	4892 (180 t) 7000 (150 t)	4907 (180 t) 7000 (150 t)	4650 (120 t)	7871 (132.6 t)	10371 (150 t)
- w/o payload	18864	18654	14200	16050	н.д.
Required runway length, m	3000	3000	3000	3100	3000

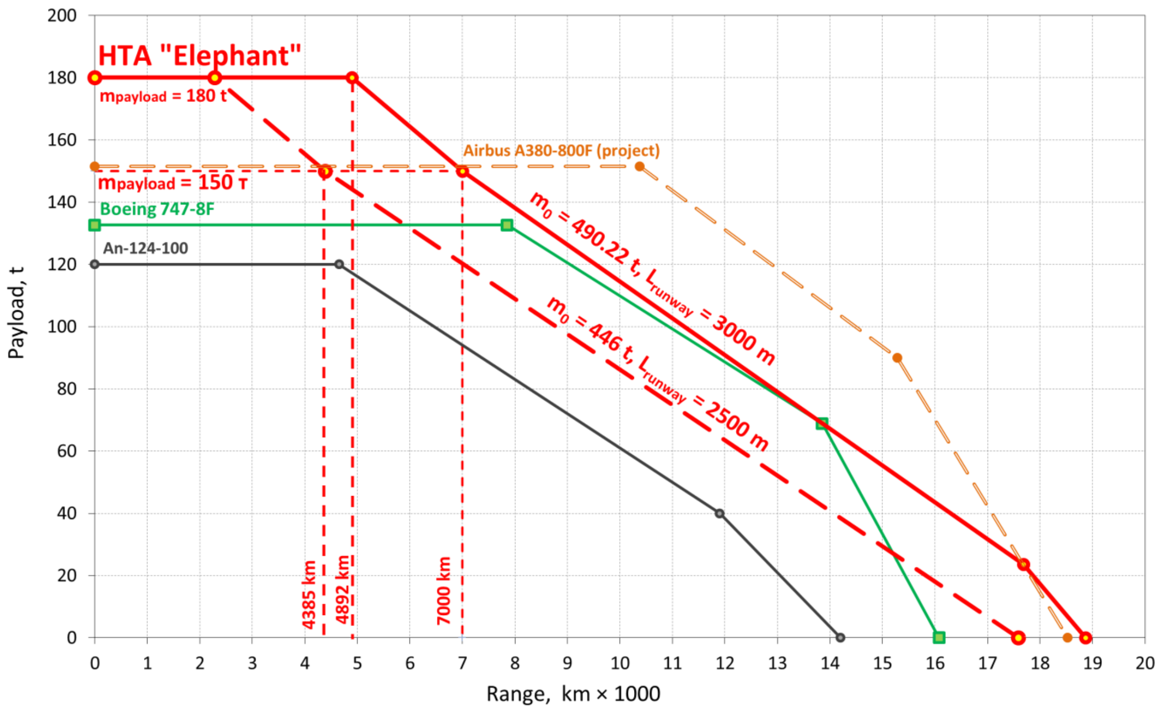

Figure 16: Payload-range diagram for the HTA "Elephant" in comparison with modern cargo aircraft

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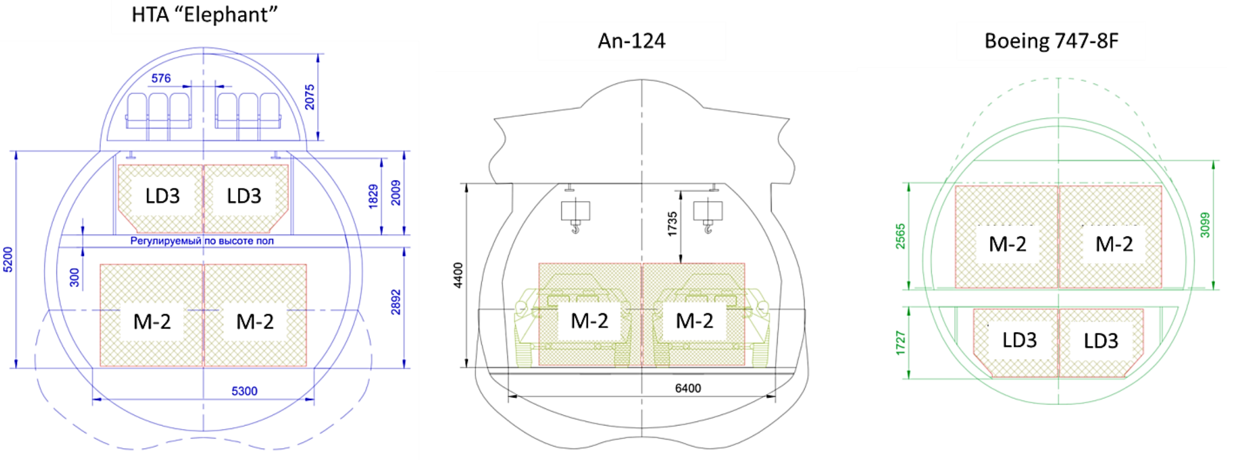

Figure 17: Double deck cargo load of the HTA “Elephant” in comparison with An-124-100 and Boeing 747-8F

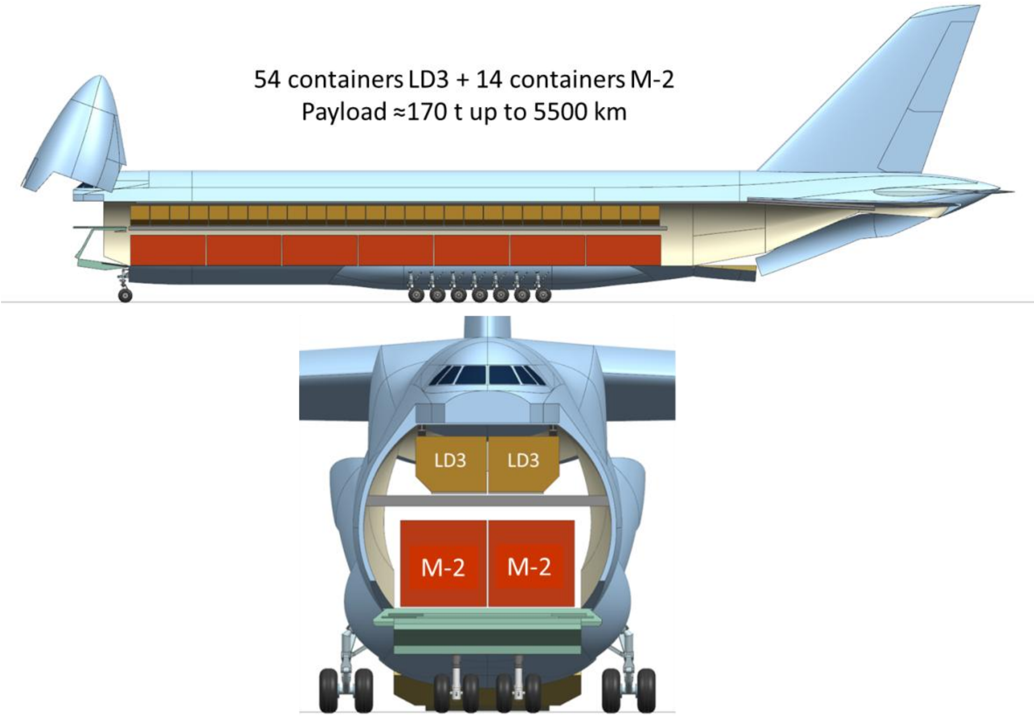

Figure 18: ULD transportation capabilities of the HTA “Elephant” (example of cargo load)

6. Conclusion

This paper reviews the results of conceptual studies of the new heavy transport aircraft for transportation a wide range of cargoes, including heavy and oversized ones.

In the process of conceptual design, the optimal geometrical and weight parameters of the aircraft were determined, ensuring the transportation of 150 t payload at 7000 km range with cruise speed 850 km/h and required runway length 3000 m.

The wing aerodynamic layout is designed to meet the specified requirements and imposed restrictions. It is shown that designed wing provides a flight with M_{cruise} = 0.8-0.82 in the range of C_L~0.5÷0.55. The aircraft layout has a estimated L/D_{MAX}≈19 at M=0.8 and natural number Re=55×10^6.

The results of the flight performance calculations show that heavy transport aircraft with conventional configuration and given geometric, aerodynamic and weight parameters ensure the transportation of goods with high fuel efficiency while maintaining the possibility of transporting oversized cargo (like the An-124), which is absent on classic “freighters” – Boeing 747-8F and Airbus A380-800F.

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References

[1] Bolsunovsky A.L., Buzoverya N.P., Karas O.V., Skomorohov S.I. An Experience in Aerodynamic Design of Transport Aircraft. Paper ICAS 2012-2.9.3, 2012. URL: http://www.icas.org/ICAS_ARCHIVE/ICAS2012/PAPERS/479.PDF

[2] Arutyunov A.G., Dydyshko D.V., Endogur A.I., Kuznetsov K.V., Tolmachev V.I. Transport aircraft development prospects // Trudy MAI. 2016. #90. URL: http://trudymai.ru/eng/published.php?ID=74704

[3] Smotrova S.A., Naumov S.M., Smotrov A.V. Tehnologii izgotovlenija silovyh agregatov aviacionnyh konstrukcij iz polimernyh kompozicionnyh materialov (Manufacturing technologies of aircraft structure units from polymer composite materials) – Moscow, TEHNOSFERA, 2015. – 216 p.

[4] Torenbeek E. Advanced Aircraft – Conceptual Design, Technology and Optimisation of Subsonic Civil Airplanes. Wiley, Chichester, 2013. – 436 p.

[5] Nicolai L., Carichner G. Fundamentals of Aircraft and Airship Design: Volume I – Aircraft Design, AIAA Educational Series, Reston, USA, 2010. – 933 p.

[6] Byushgens G.S. Aerodinamika i dinamika poleta magistral’nukh samoletov (Aerodynamics and flight dynamics of passenger aircrafts) – Moscow-Pekin, Izdatel’skii otdel TsAGI, 1995. – 772 p.

[7] Jakubovich N.V. Supergiganty An-124 “Ruslan” i An-225 “Mriya”. “On zhe russkij!” (Supergiant aircrafts An-124 “Ruslan” and An-225 “Mriya”. “It’s Russian!”) – Moscow, Eksmo, 2016. – 128 p.

[8] Boeing Company. 747-8 Airplane Characteristics for Airport Planning. D6-58326-3. Чикаго: Boeing Company, декабрь 2012. URL: http://www.boeing.com/assets/pdf/commercial/airports/acaps/747_8.pdf

[9] A.L.Bolsunovsky, N.P.Buzoverya. Transonic Wing Design Using Inverse and Optimization Methods, Journal of Advanced Engineering Design, vol.40 №1/2000.

[10] Norris G., Wagner M. Airbus A380: superjumbo of the 21st century. Zenith Press, 2010. – 160 p.