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FAST AERODYNAMIC MODEL FOR DESIGN TECHNOLOGY

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Abstract. An innovative IT-based technique of Fast Aerodynamic Computations is offered for the analysis of airliner aerodynamic characteristics in cruise flight, which is crucial from the effectiveness standpoint. A typical airliner configuration “wing + fuselage + tail” is taken for the inquiry. The technique contains integral parts for layout generation and evaluation of aerodynamic characteristics. The replicative artificial neural networks and dimensionality reduction techniques are employed as the main design tools. The aerodynamic database was formed by a CFD-code BLWF-58, enabling analysis of transonic airflow about the aircraft with regard to viscosity effects. Integration of the above components helped produce the Fast Aerodynamic Model, which serves to determine various aerodynamic characteristics. The proposed technology supplemented with relevant databases of real objects can be used for the development of feasible practical codes.

1. INTRODUCTION

The existing practice of developing new aircraft leans upon data of approximately 2.5 million aerodynamic experiments[1]. The role of math modeling here can hardly be overestimated as it allows us to reduce drastically the aircraft development cycle and enables a right decision on the new aircraft production strategy.

Despite the rapid development of computers and computational techniques, CFD-analysis of aerodynamic characteristics is still time-consuming which hampers aerodynamic design of a large number of aircraft layouts. Beside considerable computational resources, aerodynamics analysis requires highly-skilled specialists experienced in construction of complex 3D computational grids. The case is even worse for multidisciplinary analysis, which deals with high-dimension problems with thousands of design variables and their relationships.

The above reasoning constrains the employment of the CFD codes for the purposes of aerodynamic/aeroelastic analysis and aircraft R&D and calls for the development of innovative technologies for aerodynamic design enabling unlimited real-time computations of guaranteed accuracy. These new aerodynamic design technologies would reduce employment of CFD analysis and numbers of wind tunnel tests although helping the researcher make an optimal decision on the aircraft layout.

The multidisciplinary Fast Computing Technology (FCT)[2–4] appears pretty promising for the solution to the problem. The FCT employs advanced solutions in both mathematics and Information Technologies (IT) such as data analysis and fusion, artificial intelligence, etc. for the development of object-oriented design techniques and real-time modeling.

This paper offers an aerodynamic design FCT technology based on synergy of aerodynamic analysis, IT, and math techniques. Practical methods and math models derived from this FCT technology are to be used in airliner computer-aided designing as they retain advantages of engineering approach (quick-action, simplicity, robustness, etc.) yet providing accuracy good enough for the preliminary phase of aerodynamic design.

2. FAST AERODYNAMIC COMPUTING

A typical airliner configuration “wing + fuselage + tail” is taken for the inquiry (figure 1) aimed at finding the airliner aerodynamic properties at cruise flight, which is crucial from the effectiveness standpoint. The proposed approach implies

- employment of CFD-codes for the mass computations of aerodynamic characteristics for a variety of airliner layouts throughout the flight envelope;
- construction of the Fast Aerodynamic Model (FAM) by approximation of the data obtained from the CFD analysis.

Once constructed, the FAM is widely used for further aerodynamic design. It employs inputs such as the airliner 3D geometry and flight parameters (the Mach and Reynolds numbers, angles of attack and slip, and horizontal tail setting).

The FCT approach implies the following:

2.1. Decision on airliner principal 3D geometry parameters

A detailed description of aircraft 3D surface is defined as a high-dimension vector comprising thousands of parameters, most of them meaningless when considered independently. Nowadays techniques give no way to approximation of functions of this many parameters. A good solution was found through a so-called **Aircraft Geometry Model** (AGM) reducing drastically the dimensionality of aircraft 3D surface. The AGM is quite adequate at describing the airliner layouts yet employs a relatively small number of integral geometry characteristics (parameters of the model) which account for the crucial airliner aerodynamic and design properties and have always been used by aerodynamicists and engineers in the preliminary phase of aerodynamic design. The model is so constructed that variation of its parameters within the assigned limits enables accurate and detailed description of aircraft, both available and under development, analyze their aerodynamic characteristics and make comparative analysis of rather similar layouts.

2.2. Math model for the aircraft surface

The math model for the aircraft surface is based upon a number of assumptions made on the geometry of aircraft components and their mutual arrangements; sets of airfoil sections descriptions and overall layout integral properties considered as a multitude of model parameters; sets of restrictions imposed on the values of the parameters; surface reconstruction algorithms enabling a detailed description for the layout from values of the model parameters; as well as sets of additional integral properties and their calculation algorithms based on the model parameters values.

The model comprises component parts, or sub-models to describe the fuselage, wing, and empennage and their mutual arrangement within the layout. The description makes use of the Cartesian rectangular coordinates *OXYZ*, where the *OXZ* is the airliner plane of symmetry, while the *OXY* plane passes through the center (in the height) of the fuselage cylinder part (Figure 1). The fuselage coordinates coincide with the base coordinate system of the airliner.

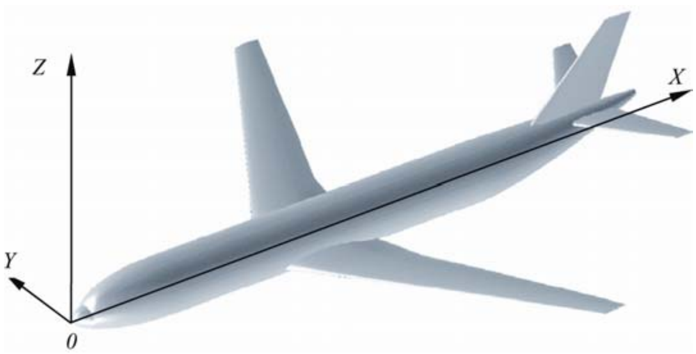

Figure 1. The airliner base coordinate system

The fuselage sub-model is given by geometries of the upper, bottom, and side longitudinal lines and shapes of cross sections perpendicular to the *OX* axis. The main parameters which explicitly determine the fuselage shape are the lengths of its nose L_{nf}, tail L_{tf} , and central L_{cf} parts; its maximum height $h_{\max}$ and width $d_{\max}$; the tail section bend z_t; and parameter ε of cross sections shapes. The nose section lines (Figure 2) are given by 10-parameter analytic functions (incl. L_{nf}, $d_{\max}$, $h_{\max}$). The tail section lines (Figure 2) are given by 8-parameter analytic functions (incl. L_{nf}, L_{tf}, L_{cf}, $d_{\max}$, $h_{\max}$, z_t). The central section of the fuselage is a cylinder. The cross sections outlines are described analytically and comprise 4 parameters with ε among them. In this case ε does not differ throughout the fuselage cross sections. The other three parameters are determined from the assigned longitudinal outlines of the fuselage.

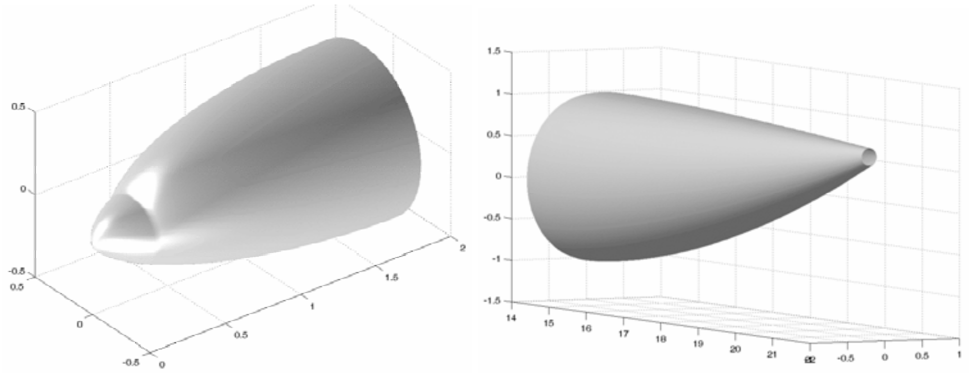

Figure 2. Shapes for the nose and tail sections surfaces

The wing sub-model is described by its planform (Figure 3), half-wing twist and strain, arrangement of airfoils sections at prescribed wing stations, and shaping airfoil outlines at arbitrary wing stations. The wing is described in the $O_wX_wY_wZ_w$, coordinate system, where the $O_wX_wZ_w$ plane is aligned with the airliner base plane OXZ and coincides with the wing plane of symmetry. The wing base plane $O_wX_wY_w$ is perpendicular to the airliner base plane OXZ and comes in parallel with the OXY plane of the airliner; the origin O_w matches with the front point of wing center chord. Considered are wings with rectilinear leading edge (LE) and an extension on the trailing edge (TE). The wing planform, i.e. the wing base-plane projection is determined by its span b_w, the sweepback angle at quarter-chord of the base trapesoid χ_{w25}, the sweepback angle at TE extension χ_{wTE}, the taper of the wing base trapesoid η_w, aspect ratio λ_w, the break point relative position $\overline{Y}_{KINK}$.

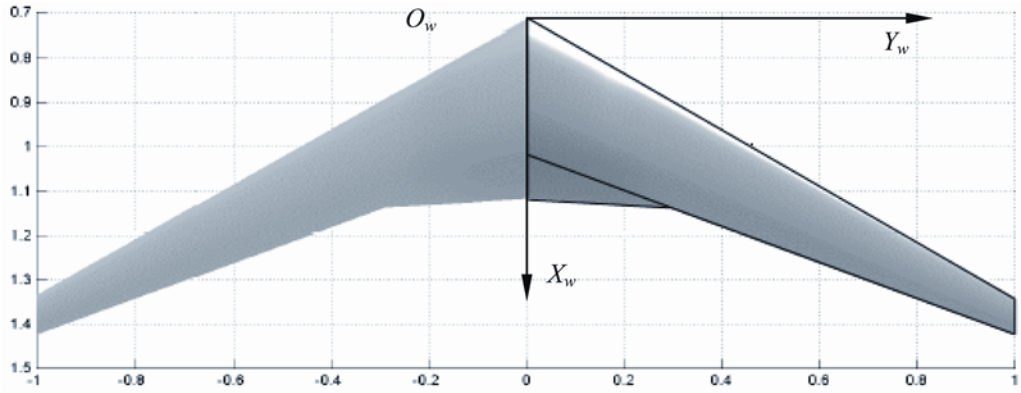

Figure 3. A typical planform of the wing

The twist-strain transformation consists in the turns of the right-hand and left-hand half-planes of the base plane $O_wX_wY_w$ (containing the right-hand and left-hand half-wings projections) about the O_wX_w axis through an angle of dihedral V; further strain of the half-wings to keep their base-plane projection $O_wX_wY_w$ intact. The wing sub-model contains 8 cross-sections Y_w=const. The first two cross-sections hold identical airfoils. **The aerodynamic airfoils** are given by equations $z_{ua}(x)$ and $z_{la}(x)$ to describe their upper and lower sections with each airfoil specified by a table of the functions values for 30 values of argument, whereas spline-interpolation is employed to determine the airfoil coordinates for the rest of values. The x coordinates are normalized along the airfoil chord. Each airfoil in this coordinate system (Figure 4) is represented by a vector of 57 values.

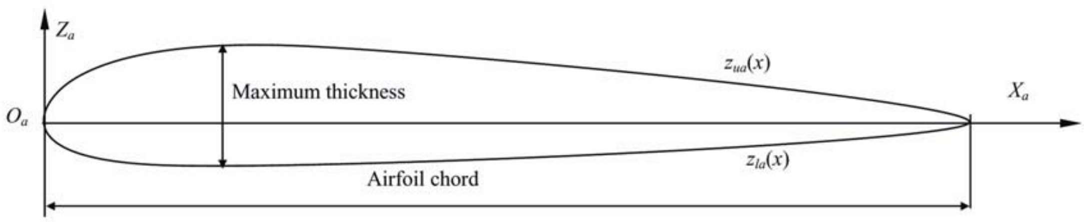

Figure 4 – Airfoil coordinate system

Airfoils are arranged at prescribed wing stations by their strain along the O_aX_a and O_aZ_a, axes, so that the chord length and maximum thickness should reach their desired values; twisting the cross-section about the front point; and further strain to maintain the wing base-plane projection $O_wX_wY_w$.

The Horizontal Tail (HT) is specified similar to the wing. The HT base-plane projection is a hexagon comprising two trapezoids symmetric about the longitudinal axis (there is no HT extension). The chords of the HT tip and mid sections come in parallel (there is no twist). The HT sub-model includes two cross-sections (mid section and tip section) to be filled up with the desired symmetric airfoils. **The Vertical Tail** (VT) is similarly described. The VT contains one half-wing whose base-plane is coincident with the airliner base plane of symmetry, and center chord passing in parallel with the OX axis.

All in all, the airliner 3D surface is specified by a 500-dimensional vector significant part of which are descriptions of airfoils sections arranged at prescribed wing sections.

3. EMPLOYMENT OF THE PRINCIPAL COMPONENT & REPLICATIVE NEURAL NETWORK METHOD FOR THE REDUCTION OF AIRLINER SURFACE DESCRIPTION DIMENSIONALITY AND GENERATION OF AERODYNAMIC SHAPES

Any design system can be conventionally divided into two modules: the first one is responsible for the evaluation of characteristics for the subject of inquiry, and the second one being generator of the designs. The artificial neural networks (ANN) are of considerable current use for fast evaluation of the design characteristics, which enables cuts in the design time significantly. And yet the problem of a reliable module - object generator is still topical for the design systems, moreover it is also necessary at the development of ANN learning sets in the aerodynamics evaluation module. Generation of objects with predetermined properties appears one of the most important feature of the module – object generator as it enables considerable simplification of the design process.

This section of the paper deals with airfoils to demonstrate application of special type ANN (replicative ANN[5]) aimed at generation of design objects with predetermined aerodynamic and geometry parameters. Replicative artificial neural networks (RANN) are supposed to reduce drastically the dimensionality of the airfoil surface under specification and come up with innovative aircraft design systems.

The RANN (or copying ANN) ranks among other multilayer perceptrons. Featuring a symmetric architecture, the networks' first and last layers have even neuron numbers equal to the length of the input vector and a "narrow neck", i.e. a mid-layer of substantially smaller dimensionality. The first two ones are accordingly named the input and output layers, while the mid one is called hidden. Figure 5 presents an architecture of the replicative ANN.

The RANN were first applied for the data compression problems[6]. Let us consider a three-layer perceptron with equal numbers of elements in the input and output layers, whereas the hidden mid-layer has substantially smaller number of elements. Let's assume that perception results in the RANN's ability to reproduce at the output the same vector that is supplied to the perceptron's input layer. The RANN thus compresses data within the area between the input layer and the hidden one and then decompresses the data back between the hidden layer and output one. Noteworthy, the hidden mid-layer elements keep representations of every vector yet shorter than its origin supplied to the input (Figure 5). The RANN actually reduce data dimensions by transferring to so-called "natural coordinates". In case of neurons with linear transfer functions such approach brings into the well-known method of principal components[7].

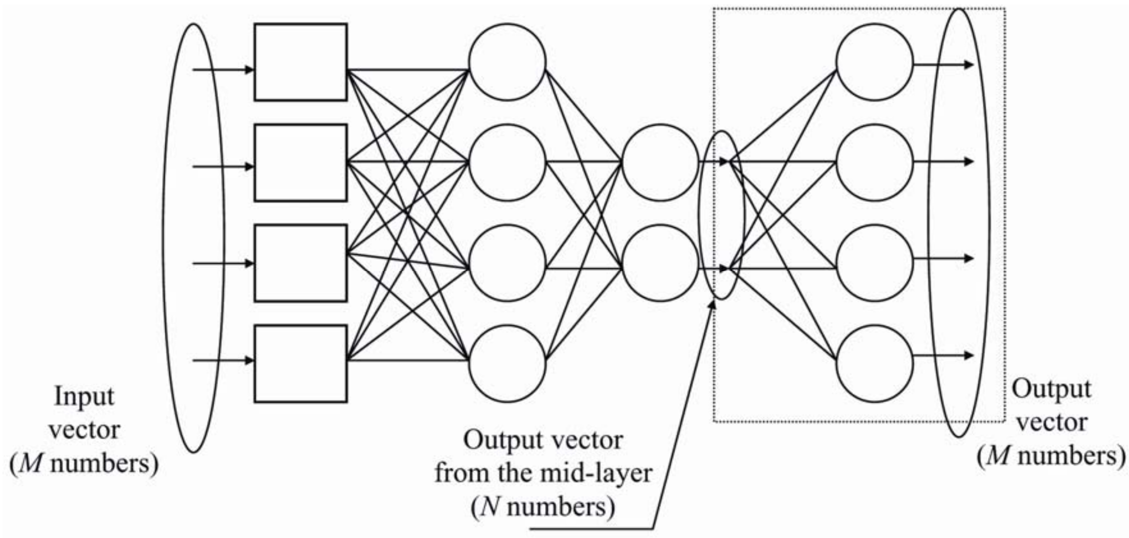

Figure 5. Replicative ANN

Another application of RANN is generation of random objects similar to those already perceived (been used for the ANN education). The random generator serves to generate points inside an *N*–dimensional area limited by assigned minimum and maximum values of the output signals in the neuron mid-layer. Once supplied to the output layer of the replicative ANN after it has been educated, the *N*-dimensional vectors transform into those of the original *M*-dimensional space corresponding to points of the natural coordinate space. Objects thus generated are rated in the same class as the original.

Let's take airfoils as an example to demonstrate solution to the following problem: there is a variety of airfoils to come through a three-layer RANN. This network features input and output layers of high dimensionality (59 inputs-outputs) and a narrow "neck" – a hidden mid-layer of substantially smaller dimension (6 neurons). Such ANN is capable of compressing data from the original input dimensionality to that of the hidden mid-layer. The challenge is to employ this educated network for further generation of new aerodynamic airfoils.

The original multitude, initially passed through the ANN, comprised 300 airfoils whose surface was assigned by 59 points. A replicative ANN employed for the problem featured linear activation functions thus reducing it to the principal component method.
The de-compressing portion of the educated network served further as airfoil generator. With this aim in view a 6-component vector was supplied either to the hidden mid-layer output or to the input of the output layer (what is the same). These vector components have random distribution and are limited by extreme values of corresponding components from the original multitude, i.e. fall within a dense set of compressed data. This results in a 59-component vector at the output layer setting a new just generated airfoil. Figure 6 gives a schematic illustration of the generation process, whereas Figure 7 presents typical shapes for the airfoils thus obtained.

Generation of objects with predetermined properties is desirable for aerodynamic design. These problems are to be solved by a modified replicative ANN where some input vector components (those components setting the limitations) are supplied directly to the output layer (Figure 8). In this case the educated network is capable of airfoil generation by supplying a random vector to the mid-layer output and supplying predetermined characteristics to the corresponding input neurons.

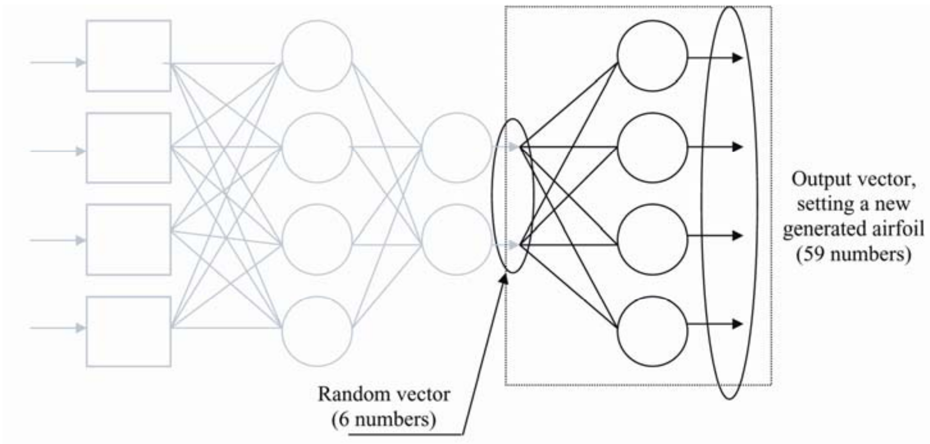

Figure 6. Airfoil generator: deriving airfoil geometry from a random vector of the compressed data space

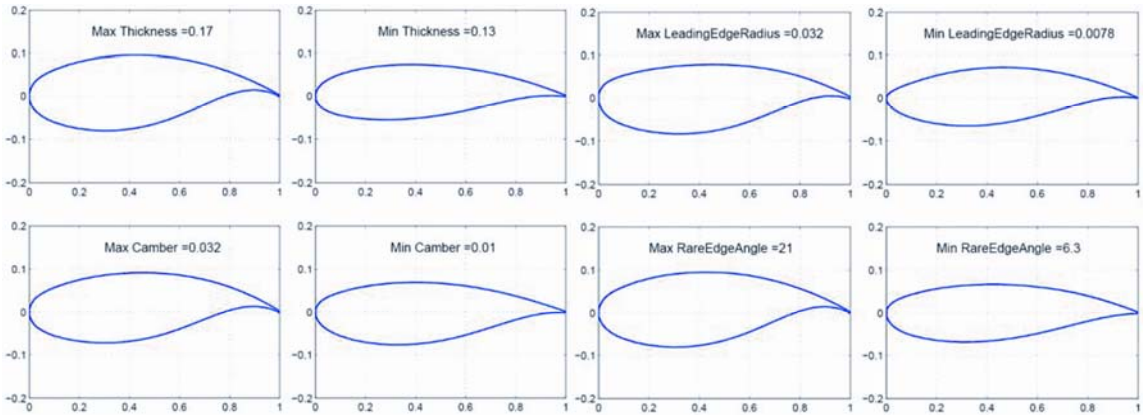

Figure 7. Random generation of airfoils within the 6D space

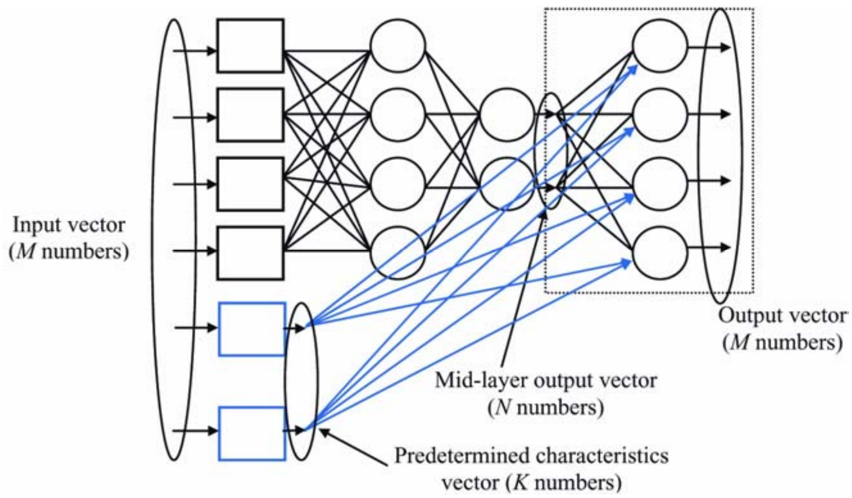

Figure 8. RANN modification. Generation of objects with predetermined characteristics

A module – generator of airfoils with limitations imposed on their geometry parameters (a set point on the upper surface) and on aerodynamic characteristics (a set value for the longitudinal moment at zero lift m_{z0}) is given here as an example of the modified networks application. This module-generator supplied a set of 1000 airfoils passing through one point and whose longitudinal moment m_{z0} offers values close to the desired one (m_{z0} = -0.086) (Figure 9). Computations, which followed the generation process, illustrated that the m_{z0} values for the given set of airfoils all fall within a range of -0.092 to -0.082.

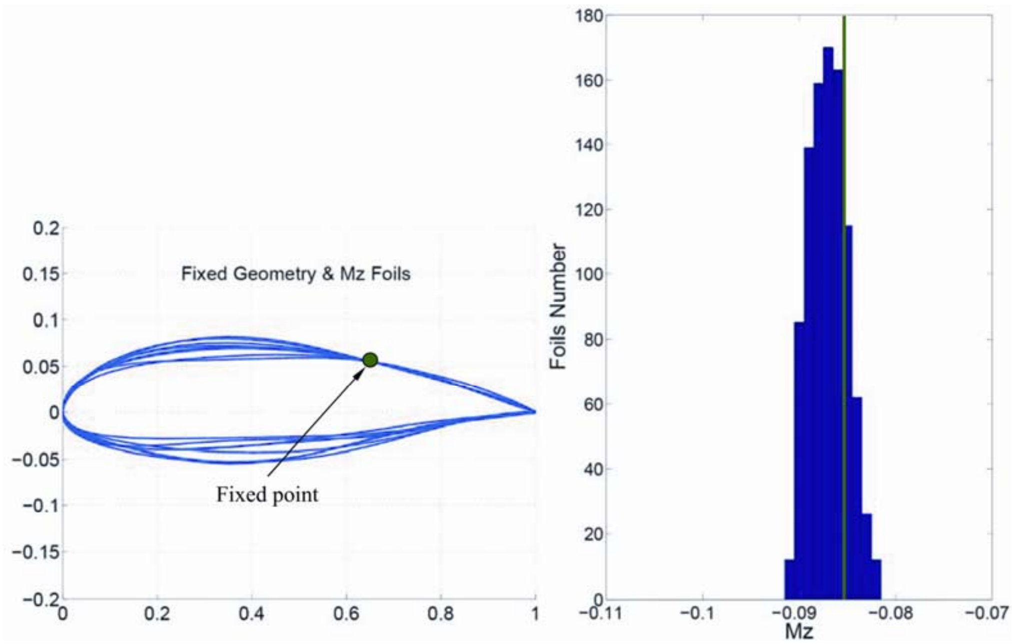

Figure 9. Set of airfoils with initially imposed limitations on geometry and aerodynamic characteristics. Geometry and m_{z0} distributions over the airfoils.

The principal component or RANN methods[8] have proven to enable a nearly ten-fold reduction in airfoil description dimensionality.

4. COMPUTATIONAL EXPERIMENTS AND DATA ACQUISITION

Over 350 000 computational experiments have been done with employment of the in-house CFD-code BLWF-58[9,10] to solve the boundary-value problem for the full potential equation of a mixed elliptic-hyperbolic type. An assumption is made on undisturbed incoming flow. The solution allows for local supersonic regions and discontinuities, i.e. isentropic shock waves.

Viscous effects are accounted for in the framework of the boundary layer approximation with a fixed location of the laminar-to-turbulent transition. Here employed is the semi-inverse method of self-consisted solution (viscous-inviscid interaction at the edge of the boundary layer) between the normal and tangential velocity components obtained for the external potential flow and internal viscous gas flow in the boundary layer. Both the external potential flow and the boundary layer flow are analyzed within one iteration. Then the difference between the chordwise velocity distributions comes to correct the normal velocity component for the next iteration. This approach has shown sufficient for flows with fully developed separation bubbles although the long-wave component convergence is relatively low and enables modeling of weak flow separations. This method has been verified and proven reliable through more complex grid techniques where the Reynolds equations were solved[11].

Input data for the computational experiments are supplied through automatic generation of aircraft layouts and airfoils with predetermined properties, which are based on the above-mentioned methods of principal components and RANN. The work yielded over 5400 different layouts with more than 5675 wing airfoils among them. On the average each layout took 70 calculations for various sets of flight conditions and parameters; see table 1 for ranges of values under variation.

Parameter	min	max	Parameter	min	max
Mach	0.6	0.84	Slip angle	0	1º
Re_{MAC}	$3 \cdot 10^6$	$3 \cdot 10^7$	Horizontal tail setting	-2º	2º
Angle of attack	-0.7º	4.8º			

Table 1. Ranges of values

5. ANN APPLICATION FOR CONSTRUCTION OF AERODYNAMIC CHARACTERISTICS APPROXIMANTS

A multilayer perceptron-type ANN with one hidden mid-layer was employed to construct approximants. The multiple of layouts was divided into two subsets with one of them (nearly 80%) used to educate the ANN, while the second one (the rest 20% layouts) came to validate data and evaluate accuracy of approximants thus obtained.

The input vectors of ANN - approximants contained parameters of the layout geometry and incident flow. A dedicated ANN was constructed for each aerodynamic characteristic, the hidden layer number of neurons varying from 7 to 15 depending on the aerodynamic characteristic under approximation. The 461-dimension ANN input vectors were intended to approximate coefficients of aerodynamic forces and moments with most part of the vector (399 parameters) determining airfoil geometry (7 cross-sections, 57 points each). The RANN-"compressed" airfoil description was used to approximate the angle-of-attack and HT setting derivatives to reduce the input vector down to an 89-dimension input vector.

6. CONSTRUCTION OF THE FAST AERODYNAMIC MODEL

Integration of the above components helped produce the so-called Fast Aerodynamic Model (FAM) which serves to determine various aerodynamic characteristics (lift and lateral force coefficients; pitch, roll, and yaw moments; profile-drag, induced-drag, wave-drag, friction-drag and total-drag coefficients; lift coefficient derivative and that of pitch moment in angle-of-attack (α) and HT setting (IHT); slip angle derivatives of the lateral force, roll and yaw coefficients; lift-to-drag ratio; spanwise load and section pitch-down moment distributions). The FAM comprises a number of sub-models, each one intended to determine but one characteristic, and employs approximation of the obtained data in the following way:

- first come preliminary approximations for several basic functions used to determine the chosen aerodynamic characteristic and dependent on the layout description and some flight parameters with the rest of the parameters fixed (e.g. the Re number and HT setting). The base functions are constructed by universal approximation techniques (methods of principal components and regression analysis, multilayer perceptron-type ANN);
- then come resultant approximations for a function dependent on the entire set of the flight regime parameters. The resultant approximations are interpolated from the base functions values (e.g. between the Re number values) and corrected with compensation factors to account for friction drag of non-lifting layout components[12].

7 ACCURACY ANALYSIS OF THE FAST AERODYNAMIC MODEL

The FAM-produced aerodynamic characteristics were verified by direct calculations by the CFD-code BLWF-58 and have demonstrated sufficient accuracy of the FAM model. The FAM relative errors (compared to the CFD-code computations) in the aerodynamic characteristics responsible mainly for the airliner fuel efficiency add up to 0.8 – 2.3%. Table 2 gives data typical of the lift coefficient (C_L), longitudinal moment (C_m), total drag (C_d) and lift and longitudinal moment derivatives in the angle-of-attack and HT setting.

Characteristic	Mean absolute error	Mean relative error (%)
C_L	0.00390	0.8
C_L^a	0.00200	1.4
C_L^{IHT}	0.00026	1.1
C_m^a	0.00470	2.3
C_m^{IHT}	0.00076	0.9
C_d	0.00030	1.5

Table 2. Data typical of the lift coefficient (C_L), longitudinal moment (C_m), total drag (C_d) and lift and longitudinal moment derivatives in the angle-of-attack and HT setting

Figure 10a shows the error density function for the drag coefficient C_d calculated at a full-scale Reynolds number Re=$3\cdot10^7$. The solid line presents difference between the C_d values obtained from direct calculations and approximation C_{d_calc}-C_{d_ANN} (σ=0.000362). The dashed line stands for normal distribution with identical RMS deviation.

The lift coefficient C_L error density function is shown in figure 10b, where the solid line also presents difference between the C_L values obtained from direct calculations and approximation C_{L_calc}-C_{L_ANN} (σ=0.0062). The dashed line stands for normal distribution with identical RMS deviation. The accuracy is apparently sufficient for analysis of aerodynamic layouts in preliminary design.

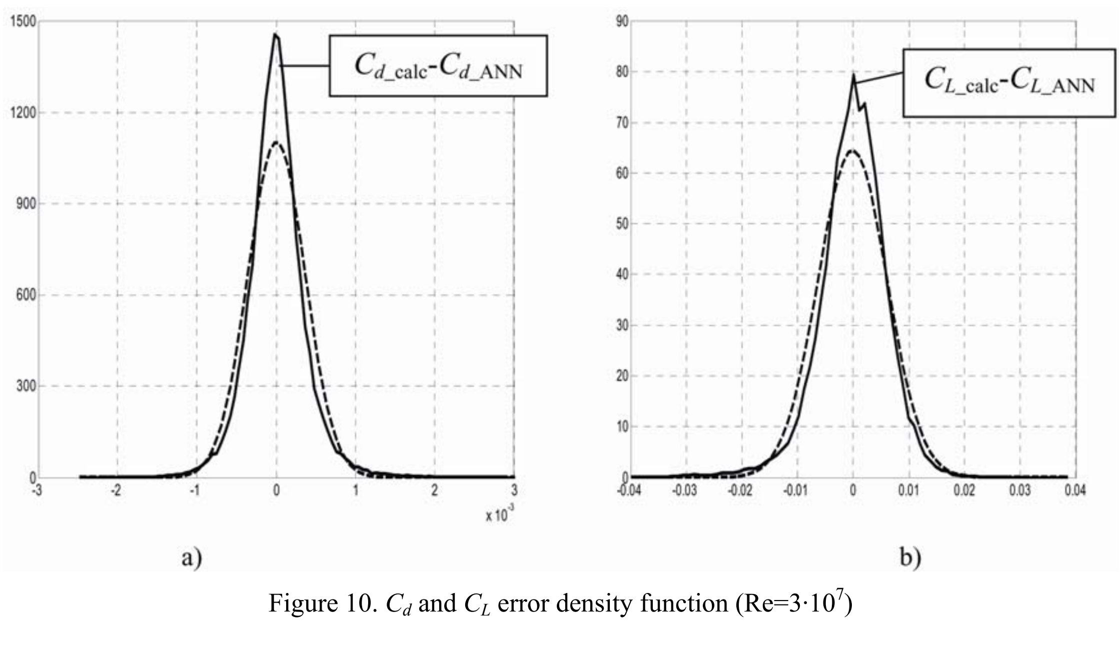

Figure 10. C_d and C_L error density function (Re=$3\cdot10^7$)

The comparison makes it evident that FAM-based computation of all the above-listed aerodynamic characteristics of a layout, both integral and distributed, for one set of flight regime parameters, on a personal computer PC PIV-1.8GHz takes dozens of milliseconds, which is several hundred thousand times faster than CFD calculations by the BLWF-58 code.

8 CONCLUSIONS

An innovative IT-based technique of Fast Aerodynamic Computations is offered for the analysis of airliner aerodynamic characteristics in cruise flight. The technique contains integral parts for layout generation and evaluation of aerodynamic characteristics.

The replicative artificial neural networks and dimensionality reduction techniques are employed as the main design tools (RANN and principal component methods). The aerodynamic database was formed by a CFD-code BLWF-58, enabling analysis of transonic airflow about the aircraft with regard to viscosity effects.

The proposed technology supplemented with relevant databases of real objects can be used for the development of feasible practical codes.

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