Artificial neural networks in panel method for solving aerodynamics problem

D Yu Strelets, A A Kataev and A L Khrustalev
Moscow Aviation Institute (National Research University), Volokolamskoe Shosse 4, Moscow, A-80, GSP-3, 125993, Russia

maksi33@gmail.com

Abstract. The authors proposed an experimental panel method combined with an artificial neural network to solve the problems of aerodynamics with minimum computational power consumption and high accuracy. A software solution based on the proposed method has been created. A comparison with experiments and other existing solutions has been made. The proposed method is intended for solving aerodynamic problems in systems of multi-criteria optimization, as well as in related problems. For example, solutions to the problem of strength and aerodynamics in the associated wing of a civil aircraft. The proposed method and software solution based on it can open new horizons in aerospace industry optimization calculations.

1. Introduction
The application of computer technologies covers a wide sphere that does not exclude mathematical modeling.

The first samples of panel methods began to appear in the 1960s as a result of the activity of NASA and TsAGI specialists [1]. Already then, the advantages of such an approach, its promising prospects were fairly assessed. In general, these first programs were code executed in the Fortran language and implementing the aerodynamic calculation of a simulated solid body divided into finite elements with aerodynamic features assigned to each of them. The problem was solved in a linear formulation by numerical methods. In today's world, the relevance of this topic has remained unchanged, if not increased. Due to the increased computational power and new technologies in the field of artificial neural networks [10] there appeared an opportunity to create principally new software products solving complex tasks, such as the task of profiling [5,6] or the related task of aerodynamics and strength both for compressible and incompressible environments on the previously formed basis. Artificial neural networks [10] can model the behavior of complex systems. There already exist methods for automatic diagnostics of ECG and heart rate [11], flight simulation [12], for modeling of helicopter flight in vortex rings [13]. Some solutions exist for visual image recognition [14], speech [15, 16] and optimization.

In the aerospace industry there are experimental methods based on artificial neural networks, for example, in the works of TsAGI in 2007 [17] was considered an artificial neural network for the evaluation of the pilot performance of the aircraft. In 2015 the principle of biological works of human brain for modeling artificial intelligence in the interests of hypersonic aerospace industry was considered [18]. One of the works [19] shows the application of artificial neural networks for creating
a system of aerodynamic design of aircraft elements. The journal "TsAGI Science Journal"  [20] contains a collection of articles on the application of artificial neural networks in applied aerodynamics tasks.

Artificial neural networks are capable of obtaining complex dependencies in the behavior of objects, which can be used with panel methods. This article describes an accurate method of determining aerodynamic characteristics for any body shape with minimum computational power consumption. The implementation is based on a strict theory built on the properties of vortex currents. The main advantage is the introduction of breakaway currents using analytical methods to obtain points of flow separation [4], and artificial neural networks [10]. This improvement gives the opportunity to get the minimum error with the experiment — both on small and large angles of attack: for airfoils, and for bodies of complex shape. According to the calculation results, this method is the closest to the CFD results, the graphs are attached below (comparison with the experimental purges of TsAGI profiles of the 60s [3]).

Next, let's look at the task definition.

2. Problem Setting
The panel methods are based on the relative simplicity of calculation and the resulting extremely short solution time. The task was to create a method and a software solution, keeping similar to the panel methods the minimum cost of computing power and achieving comparable accuracy in comparison with CFD methods. It was approved to build the methodology and logic of the solver based on panel methods implemented in the way of solving the usual system of linear algebraic equations, with some computational cells. The achievement of the given accuracy should be provided by introduction of an artificial neural network into the chosen panel method.

Acceptable accuracy at low angles of attack (α < 5 degrees) selected by the panel method is provided initially. Upon reaching the flow breakaway modes from the streamlined surface, it was necessary to create a module to ensure nonlinearity in the dependence of aerodynamic coefficients on the angles of the attacking flow.

In addition to the above, it was necessary to develop a software complex providing for the implementation of the proposed method, automated grid construction and graphical user interface. Verify and validate the proposed solution.

Next, let’s consider the proposed method.

3. Math model and proposed method
The theory of panel calculation is not new, it has been improved, integrated for years, the result is software solutions such as PANAIR, VSPAero, Morino, etc. It is based on a technique that describes the flow of the body only in a discreet environment, i.e., eliminating flow separation currents and interference between surfaces due to the absence of turbulent currents, disturbed flows [7]. The basis of the whole method is that, knowing the geometry of the surface and setting the collocation points (collocation method), it is possible to find induced velocities on the surface and obtain a matrix of influence, and by setting the boundary conditions (nonflowing condition) it is possible to determine circulation by solving the system of equations.

\[
\frac{1}{4\pi} \sum_{j=1}^{n} q_j \Gamma_j = -q_{\infty} b \alpha (i = 1, 2, ..., n),
\]

\[
\frac{1}{4\pi} \sum_{j=1}^{n} (\hat{n} * q_j) \Gamma_j = -q_{\infty} (i * \hat{n} * \cos \alpha + j * \hat{n} * \sin \alpha),
\]

\[
b = 1,
\]

where \(a_{ij}\) — influence matrix factors, \(\Gamma_j\) — circulations \(j\) panel, \(\hat{n}\) — unit vector normal, \(i, j\) — normal unit vector components, \(\alpha\) - angle of attack, \(q_{\infty}\) — undisturbed flow rate, \(q_{ij}\) — induced speeds, which are part of the influence matrices, \(b\) — bearing capacity.
In the simplest interpretation (Discrete Vortex Method) the system of equations looks as follows: in the left part — the influence matrix, consisting of induced velocities at the points of collocation, and in the right part — mathematically expressed condition of non-leaking. In a deeper interpretation, dipoles or vortices with unknown intensities and sources with known intensities are distributed on the actual or median surface [9]. Then the equation will take the form:

\[
\sum_{k=1}^{NB} \frac{1}{4\pi} \int_{B_k} \mu \hat{n} \cdot \nabla \left( \frac{1}{r} \right) ds + \sum_{l=1}^{NW} \frac{1}{4\pi} \int_{W_l} \mu \hat{n} \cdot \nabla \left( \frac{1}{r} \right) ds - \sum_{k=1}^{NB} \frac{1}{4\pi} \int_{B_k} \sigma \left( \frac{1}{r} \right) ds = 0, \tag{4}
\]

where \( \mu, \sigma \) — dipoles and source intensities respectively, \( \hat{n} \) — unit vector normal.

**Figure 3.1.** Panels of body surface and vortex veil

In Figure 3.1 you can see the location of the Surface Panels (NB — Body Surface Panels) and the location of the Vortex Sheet Panels (NW — Vortex Sheet Panels).

To obtain aerodynamic characteristics, we will compile a system of linear algebraic equations (see formula (1)). The solution of the system of linear algebraic equations is iterative, being related to the calculation of the flow separation. The introduction of a flow separation means that it will affect the distribution of pressure factors over the surface.

In the first iteration the aerodynamic characteristics are calculated without considering the influence of flow separation. Further, for all body cross-sections along the flow for each cell of the calculation grid it is necessary to calculate the factor of flow separation influence. The step of integration when dividing by a section model is selected based on the size of the calculation grid. For each selected section it is necessary to make a vector of parameters to be transmitted to the artificial neural network of the following type:

\[
\Gamma_i, \alpha, H_1, H_{i,1}, \ldots, H_i, \tag{5}
\]

where \( \Gamma_i \) — circulation value in the cell of the calculation grid for which the flow separation factor is calculated, \( \alpha \) — angle of flow, \( H_i \) — sectional thickness

The resulting vector is transmitted to an artificial neural network built on the perceptron principle:
The values obtained at the output are used to correct the right side of the equation system. After making corrections, we conduct the second iteration of the solution of the system of linear algebraic equations.

As a result of the solution of the system of linear algebraic equations considering all factors, we get the values of the circulation belonging to each cell [8], as well as the values of pressure coefficients at the collocation points, knowing the induced speeds in all directions and, consequently, the absolute speed in each cell. Thus, we get the integral characteristic of the lifting force factor:

\[
C_l = \frac{2}{\lambda} \sum_{j=1}^{n} \frac{\Gamma_j}{q_o b \alpha},
\]

\[
C_{l\alpha} = \frac{2\lambda}{n} \sum_{j=1}^{n} \frac{\Gamma_j}{q_o b},
\]

\[
U_i = U_{i\infty} + \frac{\partial \mu_i}{\partial l},
\]

\[
V_i = V_{i\infty} + \frac{\partial \mu_i}{\partial m},
\]

\[
U_i = W_{i\infty} - \sigma_i,
\]

\[
V = \sqrt{V_i^2 + U_i^2 + W_i^2},
\]

\[
C_\rho = 1 - \left(\frac{V}{V_{\infty}}\right)^2,
\]

where \(U_{i\infty}, V_{i\infty}, W_{i\infty}\) – dormant flow components, \(\partial l, \partial m\) — grid spacing (0X, 0Z), \(\lambda\) — elongation, \(\Gamma_j\) — circulation of the \(j\)-th panel, \(n\) is the number of cells by scale, \(C_l\) — lifting factor, \(C_{l\alpha}\) — angle of attack derivative, \(\mu_i, \sigma_i\) — dipoles and source intensities respectively.

4. Software solution
The programming language and application of paralleling, is in many ways a determining factor in determining the performance and quality of software. To create an aerodynamic solver using the proposed methodology, a C# programming language was used and GPU paralleling using CUDA technology. The final software product includes: a graphical user interface, an automatic generator of a calculation grid, a calculation module. The essence of the proposed scheme of three components (graphical user interface, automatic generator of the calculation grid, the calculation module) is to avoid user errors as much as possible, especially in terms of building a calculation grid.
Further we will consider validation of the created software solution.

5. Validation of the proposed method and software solution

In this section, a comparison of the experimental data of TsAGI for the aspect ratio of the wing $\lambda = 5$ and the data obtained by the calculated method is attached.

**Figure 5.1.** Validation of the proposed method by $C_y$ for profile B — 12% [2]

**Figure 5.2.** Validation of the proposed method by $C_x$ for profile B — 12% [2]
Figure 5.3. Validation of the proposed method by $C_y$ for profile V — 8% [2]

Figure 5.4. Validation of the proposed method by $C_x$ for profile V — 8% [2]

6. Comparison with other solutions
For greater visibility, the results of the work have also been compared with similar programs. The main objectives were to compare the linear areas of $C_y$ dependence on the angle of attack, as well as
— the areas of the flow separation currents, the calculation of which is provided, though not by most programs, but by many of them.

The results of the calculations are shown in the figure below.

![Plot](image.png)

**Figure 6.1.** Comparison of $C_y$ obtained using the proposed method, XFOIL and RFIOL [21].

This figure clearly shows how the curve obtained by the proposed method is precisely superimposed on the values obtained experimentally. Compared to other software implementations, here the curve of the function in the area of the flow separation is much more accurate. This is achieved by implementing correction factors into the equation system using artificial neural networks. After implementation, the function from the linear form assumed by the panel method took the form of a function curve taking into account separated flow.

7. **Conclusion**

As a result of the conducted researches the method and software implementation for mathematical modeling of aerodynamics was created. The method combines the technologies of panel methods and artificial neural networks. It is shown that the results obtained by applying the new method are the closest to the results of experiments conducted in wind tunnels.

For typical structures of an aircraft, the method will make it possible to calculate integral aerodynamic characteristics at small angles of attack (before the start of a stall) with minimal expenditure of computing resources (the calculation of a typical passenger aircraft together with automatic meshing on a personal computer takes about 10 minutes). In contrast to classical panel methods, the proposed solution allows determining the total $C_y$ at angles of attack from -6 to 6 degrees, and also wins in the accuracy of calculations (reaching the accuracy characteristic of CFD solvers). Unlike classical CFD solvers, the method significantly wins in terms of the minimum cost of computing resources and the
amount of labor required to prepare the problem (mesh generation, convergence studies, solver settings, etc.).

The proposed method can be used for preliminary calculations of aerodynamics at the early stages of aircraft design. Also, based on this method, it is possible to implement the solution of the inverse aerodynamic problem (optimization of the geometry for the given characteristics) in 2D and 3D settings.

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