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Aircraft Aerodynamic Characteristics Determination at Supersonic Flight Speeds

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The aircraft aerodynamic characteristics at supersonic flight modes can be determined with a high level of accuracy through testing the aircraft in wind tunnels or through time-consuming three-dimensional and analytical computational methods. However, in certain cases when the aircraft aerodynamic characteristics are already known within a given Mach number range for supersonic flight, it is possible to develop a relatively simple mathematical model for the aircraft aerodynamic characteristics at supersonic speeds using the aerodynamic properties of the supersonic wing leading edge for flight speeds $M_f \geq 1.2M$. The object of the study is the aircraft aerodynamic characteristics at supersonic flight speeds. The subject of the study is the impact of the aircraft geometric features on the mathematical model, which is used to determine its aerodynamic characteristics in the supersonic flight speed range. The study hypothesizes that to determine the aerodynamic characteristics of an aircraft at $M_f \geq 1.2$, it is sufficient to identify the values of the aircraft aerodynamic parameters at a flight speed of $M_f = 1.2$ and then use aerodynamic analytical dependencies for the supersonic wing leading edge to determine these parameters at $M_f \geq 1.2$. A mathematical model of the aircraft aerodynamic characteristics in the supersonic flight speed range was developed. Coefficients of drag polar and zero-lift drag for the reference mode $M_f = 1.2$ have been identified by the developed mathematical model. Then, the Mach number range for the aerodynamic characteristics of the NASA 1044 configuration has been extended to supersonic speeds of $M_f = 1.8 \ldots 4.0$. The results of the aerodynamic calculations, obtained in the form of dependencies of the drag polar and zero-lift drag coefficients on Mach number, and the aircraft polar plot, have been compared with known NASA data for the 1044 configuration aircraft. The average modeling error of the aircraft aerodynamic characteristics in the supersonic speed range is less than 3%.

Keywords: aircraft; airplane; aerodynamic characteristics; drag polar coefficient; zero-lift drag coefficient; lift coefficient derivative with respect to the angle of attack; mathematical model.

Introduction and Problem Statement

Determining the aerodynamic characteristics of the aircraft at supersonic flight speeds is a complex engineering task, typically addressed through experimental [1] or computational [2, 3] methods. Generally, after conducting experimental studies or calculations, the aerodynamic characteristics of the aircraft are represented in the form of polars, which are dependencies of the lift coefficient C_L on the drag coefficient C_D at different flight Mach numbers M_f.

In some cases, it becomes necessary to extend the Mach number range for the aerodynamic characteristics of the aircraft in the supersonic flight speed domain [4, 5]. Extending the Mach number range through experimental studies requires complex and expensive equipment, such as wind tunnels [6], while using modern computational methods for three-dimensional modeling demands substantial computational resources, software licenses, and calculation time. On the other hand, it is possible to develop a simple mathematical model of the aircraft aerodynamic characteristics at supersonic flight speeds by using the aerodynamic properties of the supersonic wing leading edge at flight speeds of $M_f \geq 1.2$ [7].

1. The Aim and Objectives of the Study

The aim of the work is to develop and verify the mathematical model of the aircraft aerodynamic characteristics in the supersonic flight speed range $M_f \geq 1.2$, based on the aerodynamic parameters of the aircraft at a flight speed of $M_f = 1.2$ and the properties of a sharp supersonic wing leading edge.

To achieve the stated aim, the following tasks need to be addressed:

- Develop a mathematical model of the aircraft aerodynamic characteristics in the supersonic flight speed range.
- Extend the Mach number range for the aircraft aerodynamic characteristics in the supersonic flight speed range using the developed mathematical model.
- Evaluate the accuracy of the aircraft aerodynamic characteristics modeling in the supersonic flight speed range.

2. Mathematical Model of the Aircraft Aerodynamic Characteristics in the Supersonic Flight Speed Range

The input data for the developed mathematical model are the aerodynamic characteristics of the aircraft presented in the form of polars

$$C_D = f\left(\mathrm{C_L}, \mathrm{M}_f\right), \tag{1}$$

or

$$C_D = C_{D_0} + A{C_L}^2, \tag{2}$$

where:

A is the drag polar coefficient;

C_{D0} is the zero-lift drag coefficient.

The lift coefficient C_L under conditions of continuous flow can be represented as:

$$C_L = C_L^{\alpha}\left(\alpha - \alpha_0\right), \tag{3}$$

where C_L^{α} is the lift coefficient derivative with respect to the angle of attack;

α is the angle of attack;

α_0 is the zero-lift angle of attack.

Substituting equation (3) into equation (2) yields

$$C_D = C_{D_0} + A\left[C_L^{\alpha}\left(\alpha - \alpha_0\right)\right]^2. \tag{4}$$

To solve equation (4) in the supersonic flight speed range that needs to be extended, the next dependencies have to be known

$$C_{D_0} = f\left(\mathrm{M}_f\right), \tag{5}$$

$$A = f\left(\mathrm{M}_f\right), \tag{6}$$

$$C_L^{\alpha} = f\left(\mathrm{M}_f\right). \tag{7}$$

The drag coefficient consists of two components: the friction drag coefficient

$C_{D_{fr}}$ and the pressure drag coefficient C_{D_p}

$$C_{D_0} = c_{D_{fr}} + C_{D_p}\ . \tag{8}$$

The primary drag consists of pressure drag (wave drag) at $M_f \geq 1.2$, namely $C_{D_0} \approx C_{D_p}$, which can be defined as

$$C_{D_P} = \frac{4k\overline{c_w}}{\sqrt{M_f^2 - 1}} = \frac{const}{\sqrt{M_f^2 - 1}}, \tag{9}$$

where k is the coefficient accounting for the shape of the wing profile and the nature of its flow;

$\overline{c_w}$ is the relative thickness of the wing.

It is possible to use the methodology presented in [7] for a more accurate determination of the drag coefficient.

From aerodynamics, it is known that for a sharp supersonic leading edge of the wing at $M_f \geq 1.2$, the drag polar coefficient increases approximately proportionally to $\sqrt{M_f^2 - 1}$

$$A = const\sqrt{M_f^2 - 1}, \tag{10}$$

and the coefficient C_L^α is inversely proportional to $\sqrt{M_f^2 - 1}$ [7]

$$C_L^\alpha = \frac{const}{\sqrt{M_f^2 - 1}}. \tag{11}$$

Thus, to determine the dependencies (5) - (7), it is necessary to identify the values of these parameters at the reference mode for $M_f \geq 1.2$. Using equation (1), given M_f and C_L, the values of C_D and C_{D_0} become known. Then, A can be determined from equation (2)

$$A = \frac{C_D - C_{D_0}}{{C_L}^2}. \tag{12}$$

The value of C_L^α for the reference mode can be obtained from equation (3)

$$C_L^\alpha = \frac{C_L}{(\alpha - \alpha_0)}. \tag{13}$$

Here, the value of the coefficient C_L is used at which the maximum aerodynamic efficiency of the aircraft is achieved. For α_0, it can be assumed that α_0=const.

When the angle of attack is unknown, it can be determined using the following algorithm:

– Set α at the reference mode;

– Using the developed mathematical model, determine the polars of the aircraft at supersonic flight modes that significantly differ from the reference one;

– Compare the obtained results;

– If the comparison error exceeds a predetermined threshold, repeat the sequence from the beginning.

3. Initial Data

As an example, the aerodynamic characteristics of the NASA 1044 aircraft were modelled (Fig. 1).

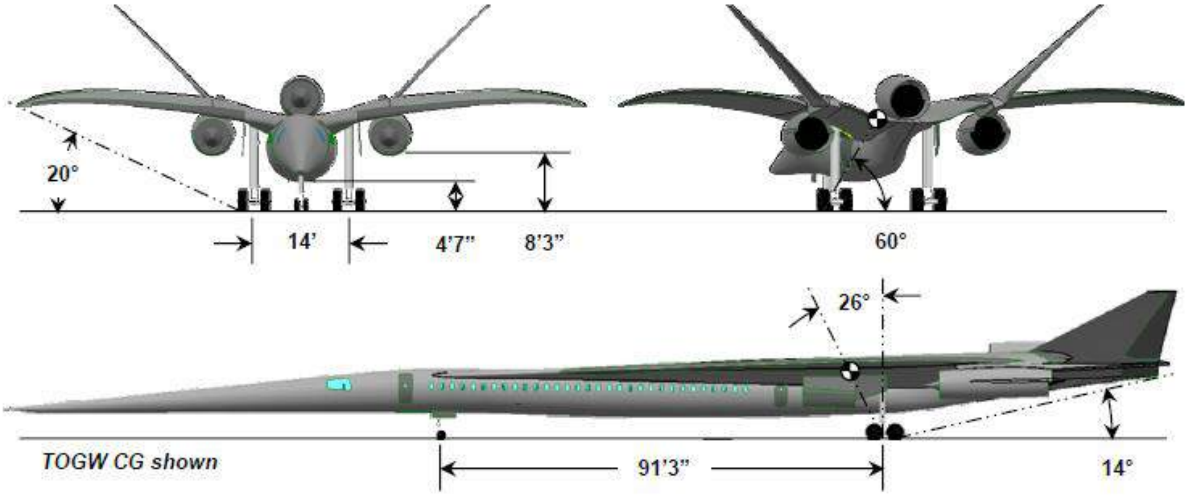

Fig.1. Geometric views of the NASA 1044 aircraft [1]

For the NASA 1044 aircraft, the polars are known in the range of M_f = 0 to 1.8 (Fig. 2).

For the aircraft whose characteristics are studied in this paper, the angle of attack in a continuous flow is known to be $\alpha = 6°$, assuming $\alpha_0 = const = 2°$.

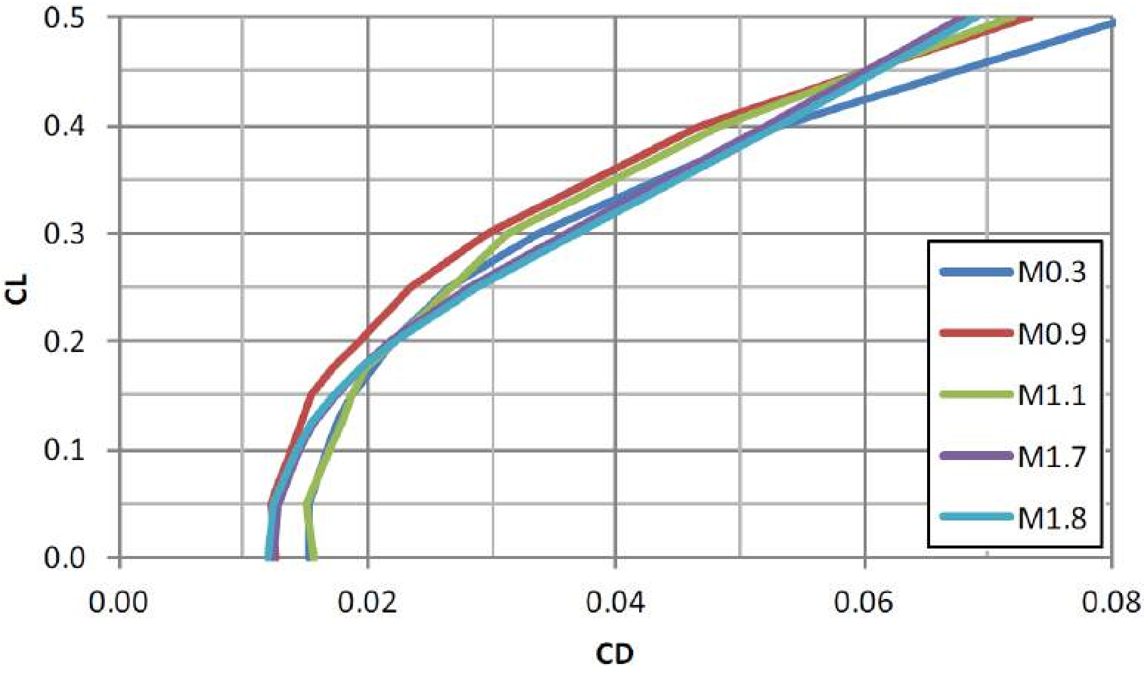

Fig. 2. Configuration 1044 drag polars [1]

4. Results of Mathematical Modelling of the Aircraft Aerodynamic Characteristics

The range of the aerodynamic characteristics in terms of the flight Mach number $M_f = 0$ to 1.8 was extended to $M_f = 0$ to 4.0 using the developed model. Dependencies (5) and (6) in the range of $M_f = 0$ to 4.0 are shown in Fig. 3.

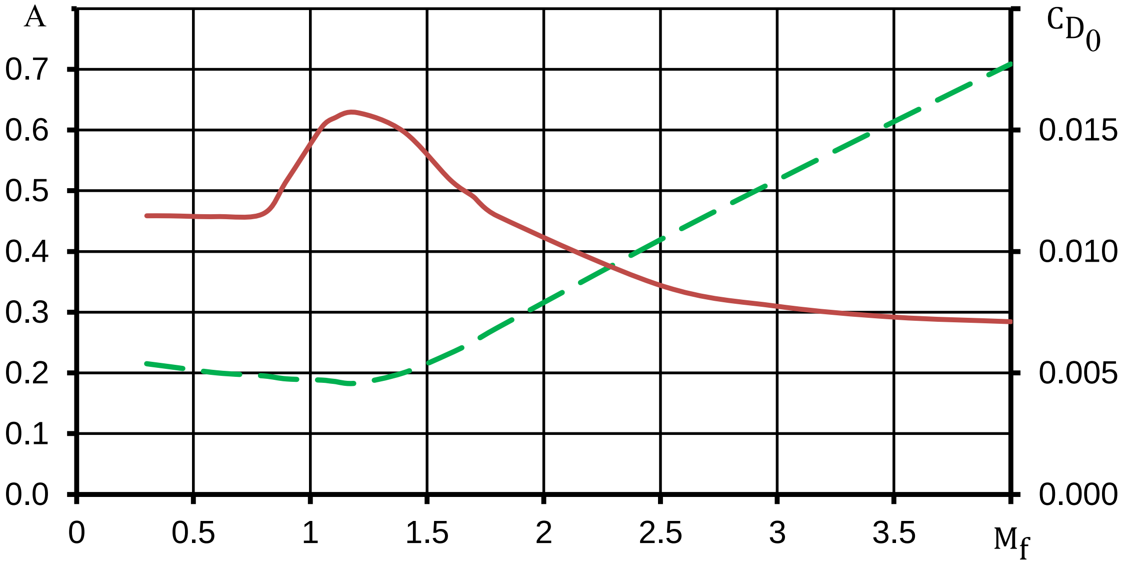

Fig. 3. Dependencies of the drag polar coefficient and zero-lift drag coefficient on the Mach number: —— – zero-lift drag coefficient; — — – drag polar coefficient.

Configuration 1044 drag polars in the range $M_f = 0$ to 4.0 are shown in Fig. 4.

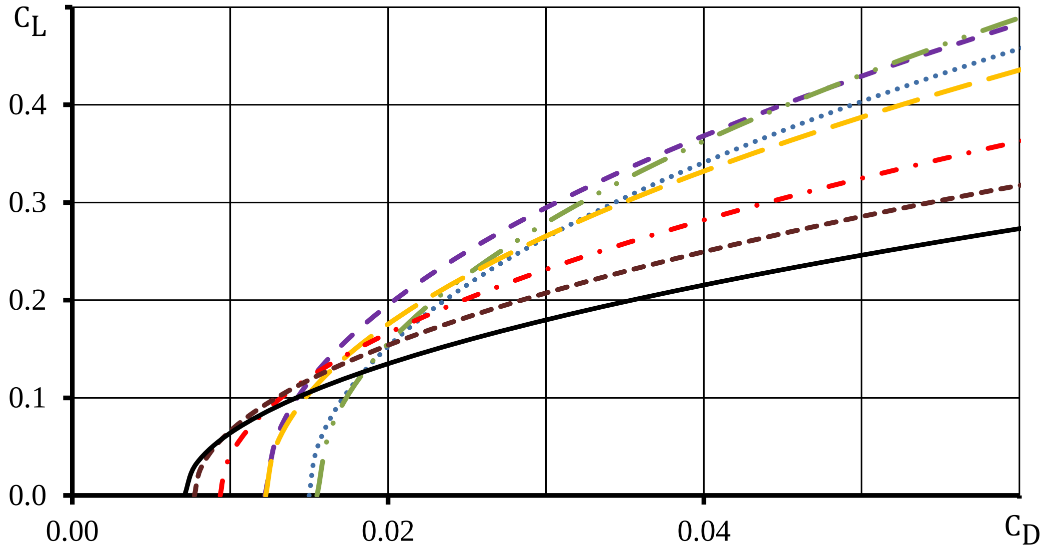

Fig. 4. Aircraft drag polars: ⋯⋯ – $M_f = 0.3$; – – – – $M_f = 0.9$; — · · – $M_f = 1.1$; — — – $M_f = 1.7$; — · — – $M_f = 2.5$; - - - - – $M_f = 3$; —— – $M_f = 4$

It can be seen from Figs. 3 – 4, that the aircraft aerodynamic characteristics at $M_f = 1.8...4$ qualitatively correspond to the aircraft characteristics with supersonic flight speeds.

5. Accuracy Assessment of the Aerodynamic Characteristics Modeling

The accuracy of the aerodynamic characteristics modeling was assessed by comparing the simulation results with the data from reference [1]:

– drag polar coefficients and zero-lift drag coefficients for known values at $M_f = 1.7$ and $M_f = 1.8$ (Fig. 5);

– drag polar of the aircraft at $M_f = 1.7$ (Fig. 6).

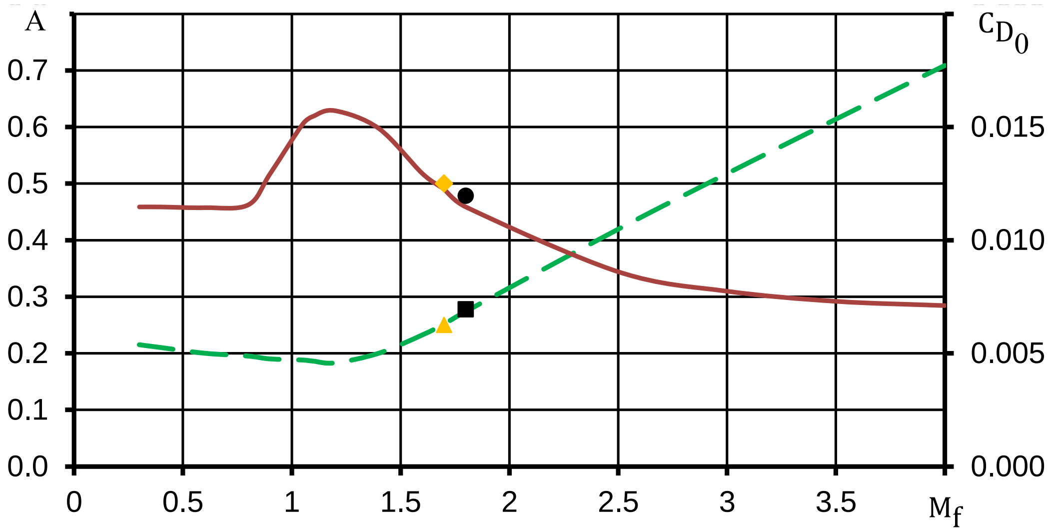

Fig. 5. Comparing the modeling results of the dependencies A and C_{D0} on the Mach number with the data from the reference [1], shown as points:
——— – $C_{D0} = f(M_f)$; — — – $A = f(M_f)$;
▲ – A at $M_f = 1.7$; ■ – A at $M_f = 1.8$; ♦ – C_{D0} at $M_f = 1.7$; ● – C_{D0} at $M_f = 1.8$.

Fig. 5 shows that the difference between the simulated results for A and C_{D0} and the known data is less than 3%.

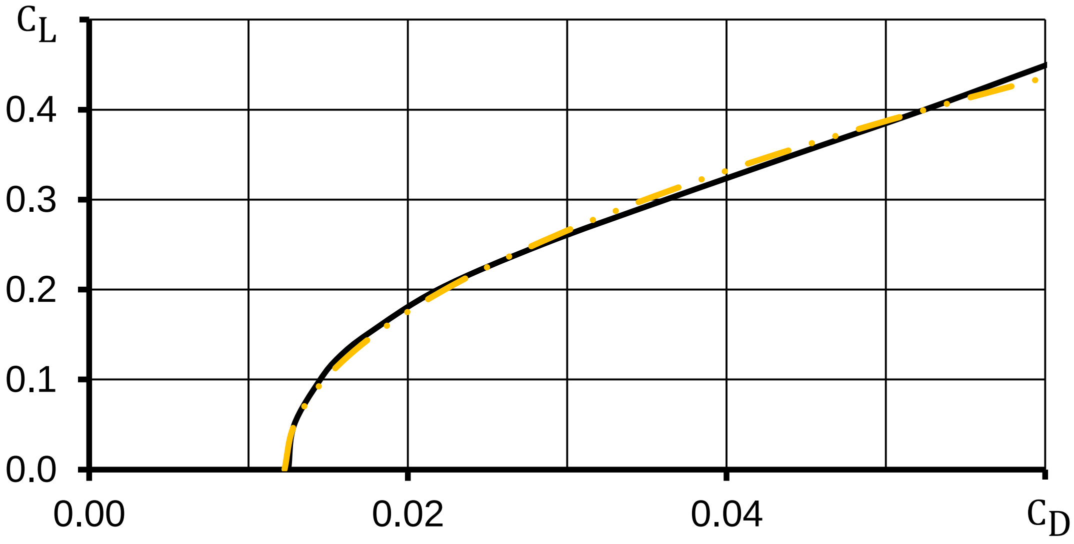

Fig. 6. Comparing the modeling results of the aircraft polar at $M_f = 1.7$ with the known data: ——— – the data from the reference [1]; — · · – simulated calculated values

Fig. 6 shows that the average calculation error is less than 2%.

Conclusions

1. The mathematical model of the aircraft aerodynamic characteristics in the supersonic flight speed range was developed. Its peculiarity is the possibility of expanding the Mach number range of the aircraft aerodynamic characteristics without additional extensive numerical calculations and experimental studies.

2. The range of M_f for the aerodynamic characteristics of the NASA 1044 aircraft was expanded from M_f = 0 to 1.8 to M_f = 0 to 4.0 using the developed mathematical model.

3. The accuracy assessment of the mathematical modeling results for the NASA 1044 aircraft aerodynamic characteristics was evaluated by comparing the calculation results with NASA data. The difference between the obtained results and the available data in the modeling of the aircraft aerodynamic characteristics is less than 3 %.

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Визначення аеродинамічних характеристик літального апарата з надзвуковим швидкостями польоту

Аеродинамічні характеристики літального апарата на надзвукових режимах польоту з високим ступенем точності можуть бути визначені шляхом дослідження літака в аеродинамічних трубах, або тривимірними та аналітичними часовитратними розрахунковими шляхами. Однак в ряді випадків, коли в заданому діапазоні чисел Маха надзвукового польоту аеродинамічні характеристики літального апарата вже відомі, використовуючи аеродинамічні властивості надзвукової кромки крила при швидкостях польоту $M_п \geq 1{,}2$, можливо розробити відносно просту математичну модель аеродинамічних характеристик літального апарата для надзвукових швидкостей польоту. Об'єктом дослідження є аеродинамічні характеристики літального апарату з надзвуковими швидкостями польоту. Предметом дослідження є вплив геометричних особливостей літального апарату на математичну модель визначення його аеродинамічних характеристик в області надзвукових швидкостей польоту. Гіпотеза дослідження полягає в тому, що для визначення аеродинамічних характеристик літального апарата при $M_п \geq 1{,}2$ достатньо ідентифікувати значення аеродинамічних параметрів літального апарата при швидкості польоту $M_п = 1{,}2$ та, використовуючи аеродинамічні аналітичні залежності для надзвукової кромки крила, визначити значення цих параметрів при $M_п \geq 1{,}2$. В роботі отримана математична модель аеродинамічних характеристик літального апарата в області надзвукових швидкостей польоту. За допомогою розробленої математичної моделі проведено ідентифікацію коефіцієнтів відвалу поляри та лобового опору при нульовій підйомній силі для опорного режиму $M_п = 1{,}2$ та виконано розширення діапазону

$M_{\text{п}}$ аеродинамічних характеристик літака NASA конфігурації 1044 в області надзвукових швидкостей польоту $M_{\text{п}}$ = 1,8…4,0. Результати розрахунку аеродинамічних характеристик, які отримані у вигляді залежностей коефіцієнтів відвалу поляри та лобового опору при нульовій підйомній силі від $M_{\text{п}}$, і поляр літака зіставлені з відомими даними NASA для літака конфігурації 1044. Середня похибка моделювання аеродинамічних характеристик літака в області надзвукових швидкостей польоту складає менше 3 %.

Ключові слова: літальній апарат; літак; аеродинамічні характеристики; коефіцієнт відвалу поляри; коефіцієнт лобового опору при нульовій підйомній силі; похідна коефіцієнта підйомної сили за кутом атаки; математична модель.

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