NUMERICAL TOOL FOR SPECIFIC FLIGHT REGIMES

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Abstract

A possibility to use the numerical code, based on the hypersonic small-disturbance theory, for the studies of some special flight regimes is considered.

A numerical method based on the hypersonic small-disturbance theory, the high-incidence slender-body Sychev's theory and Godunov's method have been used to calculate the aerodynamic characteristics of two hypersonic configurations: first-stage Pegasus XL air-launched space booster and X-34 hypersonic research vehicle, at the extreme flight conditions: $2 \le M_\infty \le 9$ and $\alpha = 0 \div 360°$. Such flight conditions arise during deep-stall flight. A variety of methods are necessary to obtain the data in the whole flight range at such regimes.

It is shown that this numerical method is a tool, which covers the biggest part of aerodynamic matrix necessary for such kinds of flight. Method is reliably tested.

A comparison of these method results with the experimental data and other methods results shows the reasonable coincidence.

1 Introduction

An idea to perform the investigations presented in this paper had been initialised by the paper of Mr.Mendenhall [1]. In this paper a “post-stall flight at very high angles of attack is proposed as a means to provide a number of useful and essential benefits”. The possibility to use a deep-stall flight had been considered as a means to fly back for two different hypersonic vehicles: 1) first-stage Pegasus XL air-launched space booster and 2) X-34 hypersonic research vehicle.

Aerodynamic characteristics (C_n, C_a, and C_m) are required for $0.5 \le M_\infty \le 9$ and angle of attack range from 0° to 360° to cover the entire range of possible flight conditions during the deep-stall portion of return flight. The whole aerodynamic matrix, including extreme flight conditions, is not available. Selected wind tunnel data are available for both configurations at normal test conditions: limited Mach number and angle of attack ($0.25 \le M_\infty \le 4.5$, $\alpha = 0 \div 25°$). Moreover, the Pegasus XL return configuration has never been tested in wind tunnel nor studied analytically. Obviously, aerodynamic characteristics are missing for the high angles of attack of interest at the specific flight regimes under consideration.

Numerical method based on the hypersonic small-disturbance theory and realised as NINA-package is proposed to cover the most part of the range of possible flight conditions encountered during deep-stall flight.

2 Problem statement

A specific flight regime means that it is necessary to determine the aerodynamic characteristics of vehicles at some extreme flight conditions: Mach number, angles of attack. For example, deep-stall flight includes angles of attack from 0° to 360°. Traditional aerodynamic tools cover some restricted ranges only. This is why authors of paper [1] had used a variety of methods to obtain the data in the whole flight range of interest:

- modified experiment
- modified Newtonian method
- splines
- numerical code M3HAX
- numerical code + splines

Main purpose of this paper is to show that numerical method on the modified small-disturbance theory (Hayes’s theory and Sychev’s theory) [2–3] covers the biggest part of the range of interest: $2 \le M_\infty \le 10$ and $\alpha = 0 \div 360°$.

Two configurations: 1) first-stage Pegasus XL air-launched space booster (fig. 4) and 2) X-34 hypersonic research vehicle (fig. 5), had been considered and the numerical results had been compared with the data of [1].

3 Numerical method

A numerical method based on the hypersonic small-disturbance theory, the high-incidence slender-body Sychev's theory and Godunov's numerical method have been developed for computing supersonic/ hypersonic flows near complex aircrafts at arbitrary angle of attack. This method permits the calculation of the aerodynamic characteristics of the complex aeroplane and airspace configurations, two or more bodies placed closely and influencing each other.

3.1 Theoretical basis

Theoretical basis of the method is:

- hypersonic small-disturbance theory [2], fig. 1a;
- hypersonic high-incidence slender-body Sychev's theory [3], fig. 1b;
- new theoretical results, obtained by authors of method:
- extension of Sychev's theory to high-incidence small-sweep wings [4];
- wing blunt leading edges calculations by Sychev's theory with time-axis, directed along edge [5].

This theory reduces the 3D steady Euler equations to the 2D unsteady Euler equations (the longitudinal coordinate x is replaced by time t, and it is assumed that $u = U_\infty \cos\alpha$). This equation transformation simplifier the numerical solution of the problem.

Numerical integration of the equations is realized by the Godunov's method [6].

So, numerical method based on the theories mentioned above integrates the following equation system:

$$\begin{aligned}
&\frac{\partial \tilde{n}_0}{\partial t_0} + \frac{\partial \tilde{n}_0 v_0}{\partial y_0} + \frac{\partial \tilde{n}_0 w_0}{\partial z_0} = 0,\\
&\frac{\partial v_0}{\partial t_0} + v_0\frac{\partial v_0}{\partial y_0} + w_0\frac{\partial v_0}{\partial z_0} + \frac{1}{\tilde{n}_0}\frac{\partial p_0}{\partial y_0} = 0\\
&\frac{\partial w_0}{\partial t_0} + v_0\frac{\partial w_0}{\partial y_0} + w_0\frac{\partial w_0}{\partial z_0} + \frac{1}{\tilde{n}_0}\frac{\partial p_0}{\partial z_0} = 0,\\
&\frac{\partial s_0}{\partial t_0} + v_0\frac{\partial s_0}{\partial y_0} + w_0\frac{\partial s_0}{\partial z_0} = 0,\\
&s_0 = \frac{p_0}{\tilde{n}_0^{\tilde{n}}}
\end{aligned} \qquad (1)$$

where the longitudinal coordinate X is replaced by the time to = $X\, U_\infty \cos\alpha$.

Coordinate system is shown by fig. 1a,b

The boundary conditions on the body are:

$$\frac{\partial f}{\partial t_0} + v_0\frac{\partial f}{\partial y_0} + w_0\frac{\partial f}{\partial z_0} = 0 \qquad (2)$$

The boundary conditions on the shock wave are transformed into 2D unsteady correspondingly.

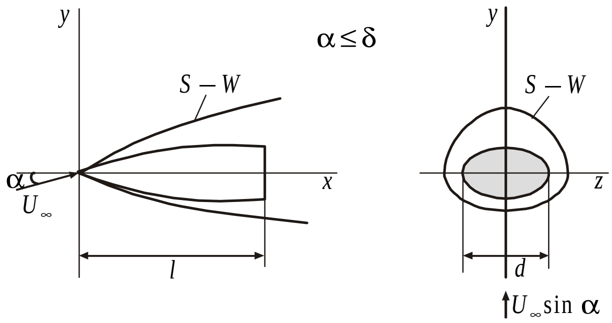


FIGURE 1a. Hayes's theory

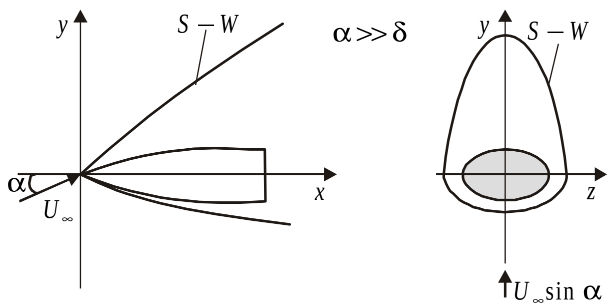


FIGURE 1b. Sychev's theory

Hypersonic slender-body theory equations (1) are integrated by Godunov's first-order approximation method [6]. Bow shock wave is the boundary of calculation region and is determined by procedure [7]. The disturbed region is confined to a body surface and bow shock wave. The calculation grid is attached to the body surface and bow shock wave. If disturbed region configuration is complex this region is divided into simple subregions.

Program code NINA (Numerical Investigation of Nonlinear Aerodynamics) is designed on the basis of the above theory.

The theoretical and numerical investigations presented in paper [4–5] show that the above theories are applicable to calculations of supersonic flows near any-swept wings in a large angles-of-attack range. The applicability range of these theories was determined and it was shown that this range is considerable largely than it was assumed in papers [2] and [3]. So, a large class of airframes can be considered using this theory.

3.2 Advantages

Advantages of numerical method based on theory [2–5] are:

- the numerical method integrating equations (1) is more stable in operation and utilisation than 3D methods because the main difficulty in using 3D methods is the arising of subsonic domains ($u < a$) where equations change the type. The method under consideration assumes that $u = U_\infty \cos\alpha$ always and the equation type does not change.
- this method permits one to solve problems with real subsonic domains such as:
- the problem of the flow on compression side of arbitrary slender airframes at high angles of attack.
- the problem of the flow near blunt leading edge of small-swept wings.

4 Method validation

The method and code are reliably tested [8–9] and it was shown that the applicability range of this method is: $2 \le M_\infty \le 10$ and $\alpha = 0 \div 360°$.

Selected examples of the method validation are shown below.

The applicability of this method to slender-body calculations at high angles of attack is demonstrated by fig. 2,3.

Pressure and density distribution on cone-surface calculated by NINA-method (solid lines) are compared with 3-D second-order numerical method (touched line) at M = 7, $\alpha = 10°;30°;50°$ (fig. 2).

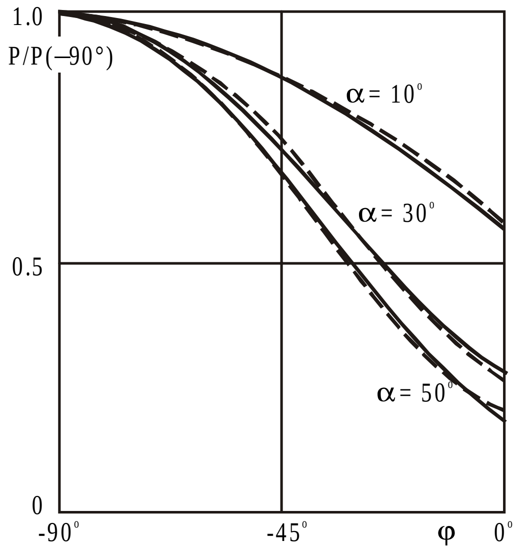


FIGURE 2. Cone at high angles of attack

Total characteristics C_x, C_y, m_z and $\bar{X}_g$ obtained by NINA method (solid lines) are compared with experimental data (points) at M = 7 and $\alpha = 0 \div 60°$. The example of NINA numerical results comparison with experimental data at $M_\infty = 7$ and $\alpha = 0 \div 60°$ is shown by fig. 3.

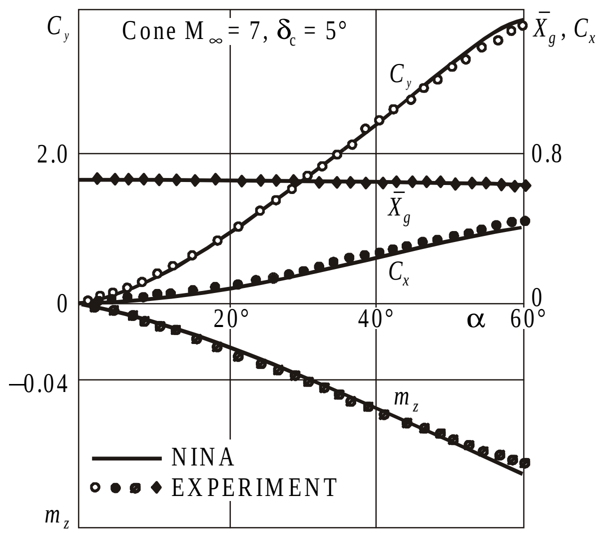


FIGURE 3. Total characteristics of cone at $\alpha = 0 \div 60°$

5 Results

The two configurations considered in this study are the same as in paper [1].These configurations are Pegasus XL first stage and X-34, which are shown is figures 4 and 5 respectively.

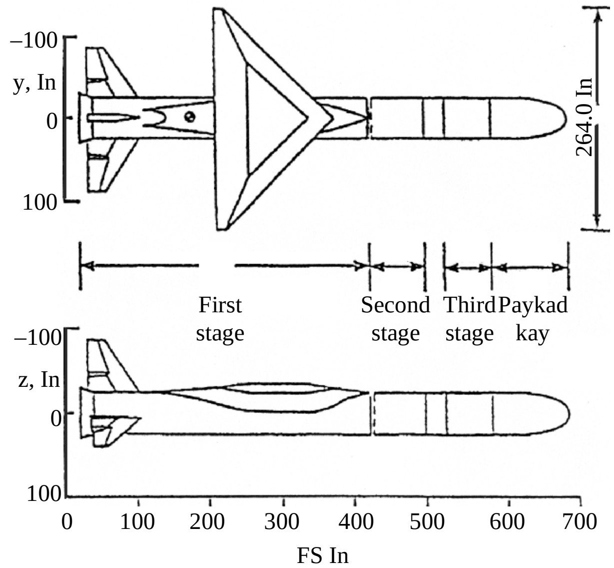


FIGURE 4. Pegasus XL configuration

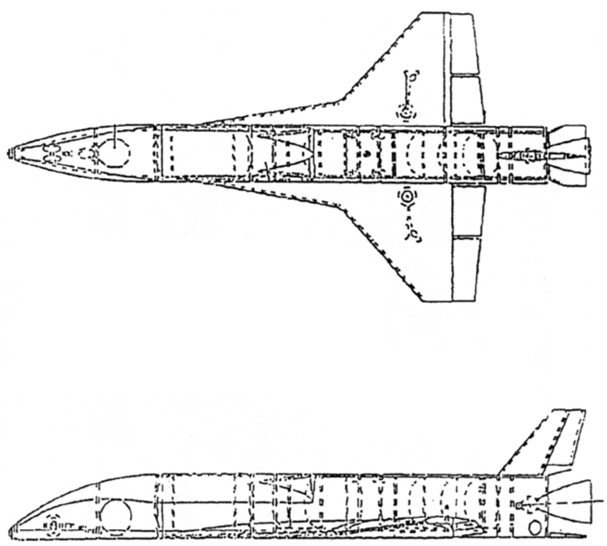


FIGURE 5. X-34 configuration

Extremely extensive aerodynamic matrix is required for such configuration to cover the entire range of possible flight conditions which may be encountered by each vehicle during the deep-stall portion of the return flight. Aerodynamic characteristics (C_n, C_a, and C_m) are required for $0.5 \le M_\infty \le 9$ and angle of attack range from 0° to 360°. The whole aerodynamic matrix, including extreme flight conditions, is not available. Selected wind tunnel data are available for both configurations at normal test conditions: limited Mach number and angle of attack ($0.25 \le M_\infty \le 4.5$, $\alpha = 0 \div 25°$). Moreover, the Pegasus XL return configuration has never been tested in wind tunnel nor studied analytically. Obviously, aerodynamic characteristics are missing for the high angles of attack of interest at the specific flight regimes under consideration.

A lot of instruments had been used in [1] to generate the adequate aerodynamics under extreme flight conditions and to simulate the deep-stall flight characteristics:
– modified experiment
– modified Newtonian method
– splines
– numerical code M3HAX
– numerical code + splines

Flight regimes range for deep-stall is shown in fig. 6, where the aerodynamic tools applied in the corresponding subranges are indicated also. The applicability range of any numerical method based on the hypersonic slender-body theory (for example NINA-code) is shaded on the same fig. 6. As it is shown by fig. 6, an analytical-numerical method based on theory [2–3] covers a big part of the range of interest: $2 \le M_\infty \le 9$, $\alpha = 0 \div 360°$.

This tool permits to calculate:
– flow fields over the vehicle;
– shock wave location;
– flow parameters distribution on the vehicle surface;
– total characteristics (aerodynamic forces and moment coefficients);
– aerodynamic loads on selected elements.

Selected aerodynamic results for the Pegasus XL first stage configuration are shown in fig. 7a,b. Cn and C_m characteristics in the range of angles of attack $\alpha = 0 \div 360°$ are shown at $M_\infty = 2$ (fig. 7a) and $M_\infty = 8$ (fig. 7b). NINA–code results are indicated by the points. The results of paper [1] obtained by the variety of methods:
– experimental results at low angles of attack, $\alpha < 20°$ (and to validate the analytical results);

– modified Newtonian method with corrections from flat plate and cylinder data at high angles of attack approaching 90°;
– a cubic spline fit between the experimental data and the high angle results,

are shown by solid line.

Two kinds of the vehicle geometry representation have been used: 1) by the sections normal to the longitudinal axis from the nose to the tail part of vehicle (direct configuration); 2) by the sections normal to the longitudinal axis from the tail part to the nose of vehicle (inverse configuration).

The results in whole range of angles of attack $\alpha = 0 \div 360°$ for any configuration are obtained as follows:

– $0° \le \alpha \le 90°$: direct configuration at

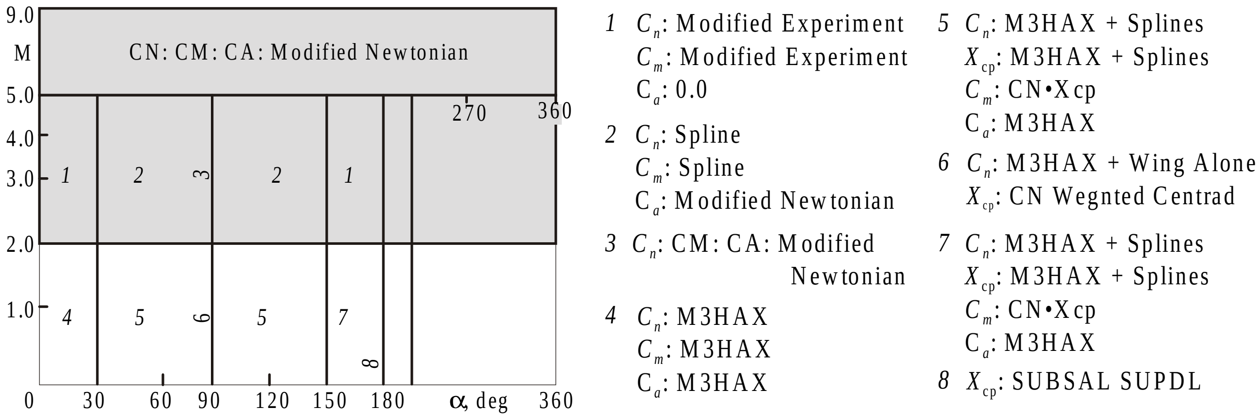
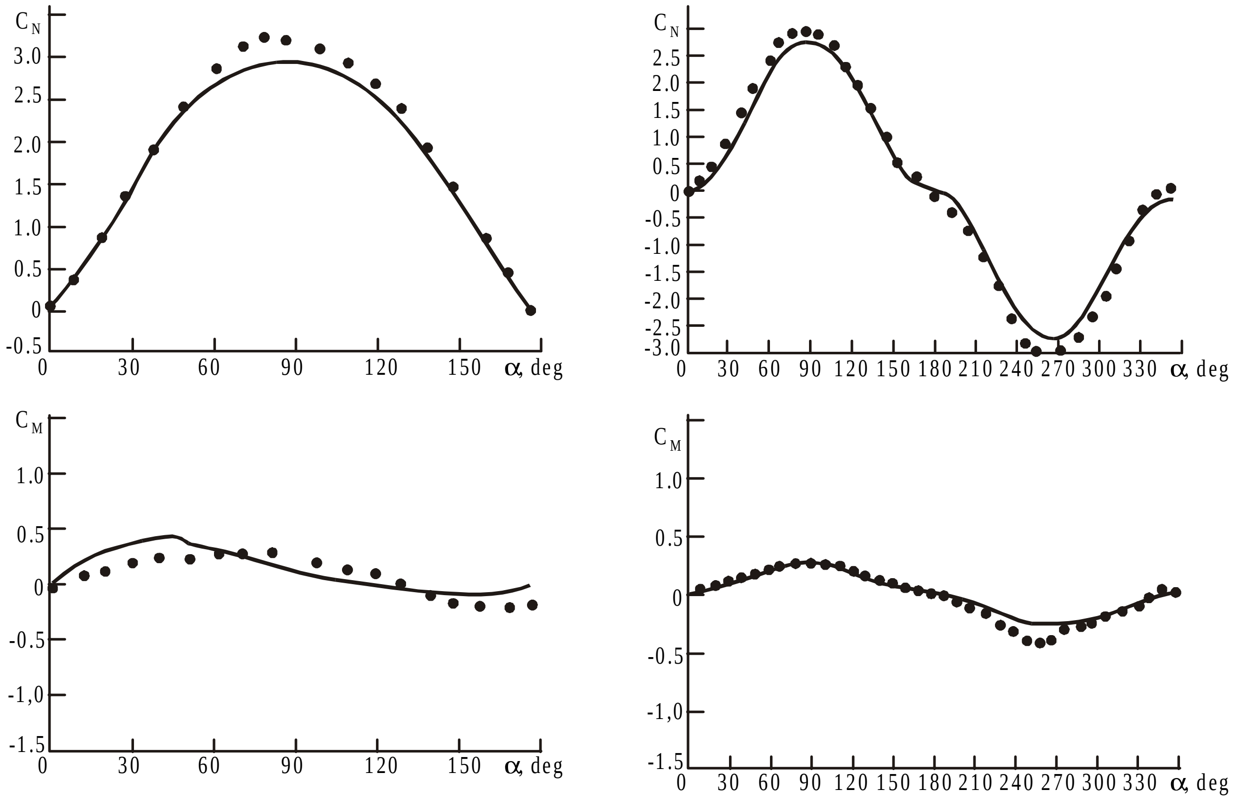


FIGURE 6. Pegasus XL stage one aerodynamic estimation procedure



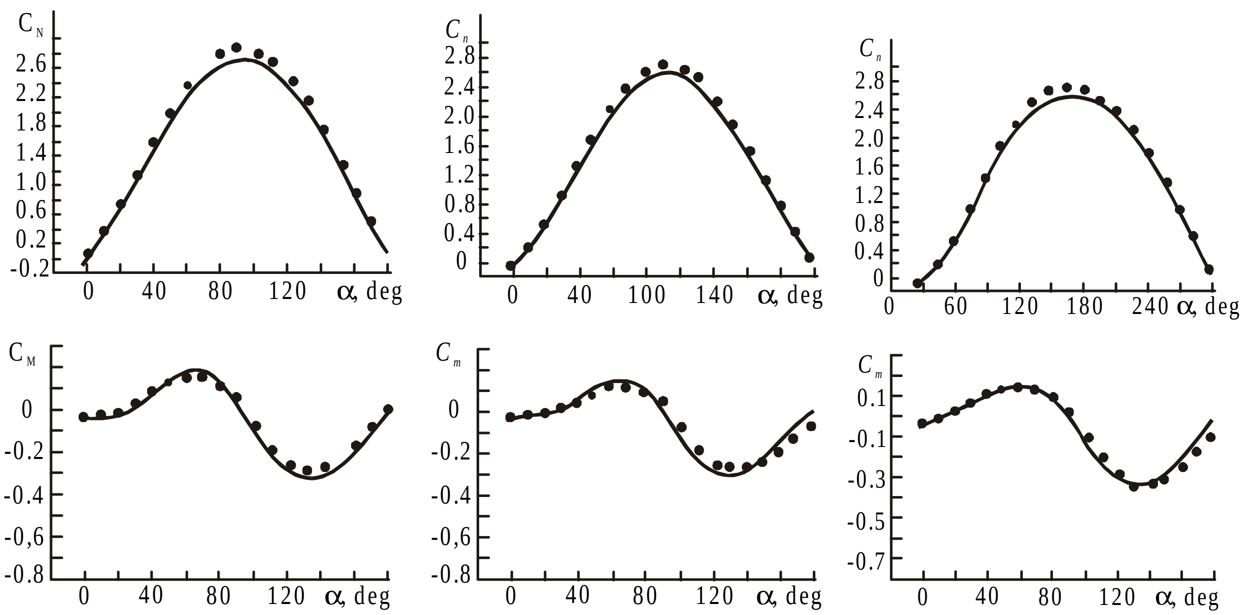
a. Mach 2.0 *b*. Mach 8.0

FIGURE 7. Pegasus XL aerodynamics

$0° \le \alpha \le 90°$,

- $90° \le \alpha \le 180°$: inverse configuration at $-90° \le \alpha \le 0°$,
- $180° \le \alpha \le 270°$: inverse configuration at $0° \le \alpha \le 90°$,
- $270° \le \alpha \le 360°$: direct configuration at $-90° \ge \alpha \ge 0°$.

The results of NINA-code are in reasonable agreement with data of paper [1]. The biggest discrepancies are observed in the range $\alpha = 240° \div 300°$ in fig. 7b. The results of [1] had been obtained by the combination of modified Newtonian method and an estimate based on three-dimensional flat plate. The symmetrical curve obtained by this methodology is a bit strange for the non-symmetrical configuration (in correspondence to the plane of wing). Such symmetrical curve can be obtained for the axi-symmetrical body with middle position of the wing. In this case the aerodynamic characteristics around $\alpha = 90°$ are the same as around $\alpha = 270°$, and the curve is symmetrical in correspondence to the point $\alpha = 180°$. But Pegasus XL has the upper position of the wing. So, the aerodynamic curves cannot be symmetrical. The methodology used in [1] doesn't permit to take into account such essential feature of the configuration. This is the reason to suppose that NINA result is more correct in this case.



a. $M_\infty = 2.74$ *b*. $M_\infty = 4.96$ *c*. $M_\infty = 6$

Fig. 8. XL-34 aerodynamics

Selected aerodynamic results for configuration X-34 (fig. 5) are shown in fig. 8a,b,c. $C_n(\alpha)$ and $Cm(\alpha)$ are presented at $M_\infty = 2.74$, 4.96, 6.00 in the α-range from 0° up to 180°. The points indicate NINA–code results. The results of paper [1] obtained by the variety of methods:

- experimental results at low angles of attack, $\alpha < 20°$ (and to validate the analytical results);
- modified Newtonian method and an estimate based on three-dimensional flat plate data at high angles of attack approaching 90°;
- a spline fit between the experimental data and the high angle results,

are shown by solid line.

The results coincidence for X-34 is quite acceptable in the whole range of consideration. $2 \le M_\infty \le 9$, $\alpha = 0 \div 180°$.

Some additional investigation has been performed to verify the data supplied by the method under consideration. Like in paper [1] the results of NINA-code applied to the Shuttle Orbiter at supersonic Mach numbers and angles of attack up to 90°. Wind tunnel data on the Shuttle Orbiter for $\alpha = 90°$ are presented in paper [1]. The Shuttle Orbiter schematically shown by fig. 9 have been calculated by NINA–code. The results are presented in Fig. 10. The configuration was calculated at $\alpha = 90°$ an Mach numbers from 2. to 4.5. The experimental data are shown by points, NINA–results – by solid line, analytical data of [1] – by touched line. The aerodynamic data obtained from three different sources are in reasonable agreement.

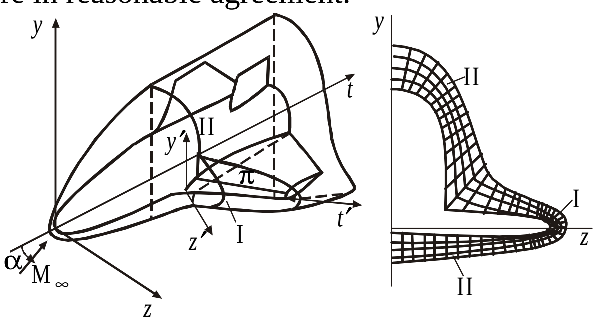


FIGURE 9. Shuttle Orbiter schematic view

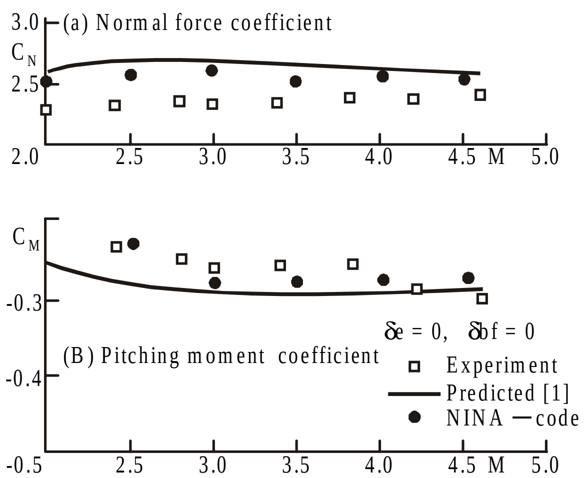


FIGURE 10. Shuttle Orbiter longitudinal aerodynamic characteristics at $\alpha = 90°$

6 Conclusions

Numerical method based on theories [2–3] has been used to solve the aerodynamic problems at very complex flight regimes, which arise during deep-stall flight of hypersonic vehicles. This aerodynamic tool provides the data in a wide range of parameters ($2 \le M_\infty \le 9$, $\alpha = 0 \div 360°$), which covers the biggest part of aerodynamic matrix of interest.

Numerical studies of two hypersonic configurations: first-stage Pegasus XL air-launched space booster and X-34 hypersonic research vehicle, have been performed. The results are compared with the data of a number of aerodynamic tools, used in paper [1].

It is shown that NINA–code results are in an acceptable agreement with data of paper [1]. In some ranges, where the data discrepancy is essential, the results of NINA–code seem more probable.

Method under consideration is reliable tested. It is an effective tool to obtain the aerodynamic data on very complex flight regimes at high angles of attack, where another methods are not applicable.

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