SOME CONSIDERATIONS ON FORMS OF AERODYNAMICS SURFACES USED FOR NAVAL MISSILES

Ionel PREDA [1], Virgil STANCIU[2], Gheorghiță TONCU[3]

Sunt prezentate unele relații propuse de autori cu scopul de a evita situațiile critice ce apar în cazul aerodinamicii rachetelor navale. Este redată legătura dintre unghiul de săgeată şi numărul Mach critic precum şi o metodă nouă de calcul predictiv pentru unghiul de săgeată. Metoda a fost aplicată la analiza pentru configurarea rachetei navale româneşti.

Authors' formulas for avoiding critical situations are given, which occur on the aerodynamic surfaces of naval missiles. The sweepback or front angle of wing is now related to critical Mach line and a different method for computing this angle is used. These formulas were successfully applied in new wings computing, based on the missile wings.

Key words: aerodynamic surface, naval missile, sweep-back angle, leading edge, trailing edge, flow.

Symbols

A = slenderness factor; b = wing span; c_e = c_{50} = wing tip chord;
c_0 = wing root chord; $D_{\max}$ = maximum diameter of fuselage;
E = shape cutting; r = taper ratio; r = taper ratio;
M = *Mach* number; S_w = wing surface.

Greek letters

ε = relative thickness**;** λ = aspect ratio; χ_0 = sweep-back angle of leading edge;
χ_{100} = sweep-back angle of trailing edge.

Indices and exponents

cr = critical; *i* = embedded; *fl* = flight;
' = reduced; *le* = leading edge; *te* = trailing edge

1. Introduction

In the aircraft design and of some missiles, the wings, empennages and/or ailerons represent the main aerodynamics components on which depends the (aerodynamic and dynamic) behavior of the object during flight [1] [2]. The projections of aerodynamic surfaces on a plane parallel with their median plane or on a reference plane have usually simple geometric forms (rectangle, trapeze or tri-

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angle) based more on constructive reasons than functional ones. But, for some naval missiles complex forms of wings, empennages and ailerons (generated by a sequence of complex curves) are used too [3]. The main form and geometric characteristics of the wing and the other surfaces are mainly established on aerodynamics considerations so that the wings, ailerons and empennages assure the necessary characteristics of flight between the speed limits established for naval missiles [4].

Theoretical and experimental aerodynamics studies established that there are many regimes and domains of air flow around wings, empennages and ailerons [5] [6] [7]. Special problems are made by the turbulent flow which diminishes the efficiency of commands for air frame, induces vibrations in mechanical systems and supplementary forces which appear and act on naval missile etc. [8] [9] [10]. Even in subsonic flight (compressible), on wings, empennages and ailerons surfaces appear local supersonic flow and turbulences which become more important when speed rises to transonic regime [11] [12].

One of the most important problems in design of air frame is represented by the reduction of efficient surface realized by appearance of turbulence and shock waves on wings, empennages and ailerons. The main method used since '40 is represented by use of boundary angle for forms of aerodynamic surfaces. Later, special devices as: shock wave breakers, apices, disks, vortex generators, spoilers etc. have been used. These expensive constructive elements are used rather for commercial aircrafts than for singular or limited use flight vehicles [11] [13] [14].

2. Correlations of most important geometric elements of aerodynamic surfaces

The most used forms on plane of wings, empennages and ailerons are those generated through straight lines (rectangle, trapezoidal and triangular or "delta"). These forms have the advantage of being easy to make with enough precision demanded by design. In subsonic compressible flight the trapezoidal form is often met. This form and its versions will be analyzed further.

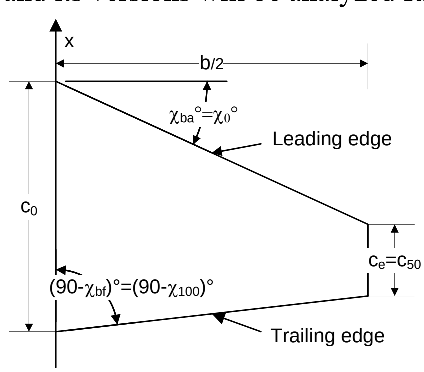


Fig. 1.1. Topview of a wing (planform)

The geometric elements of form on plane (fig. 1.1, 1.2, 1.3) which will be used for calculation are: wing surface S_w, root wing chord c_0, tip wing chord $c_e = c_{50}$, span b, sweepback angle of leading edge χ_0, sweepback angle of trailing (rear) edge χ_{100}, and the derivate parameters from Eqs. (1.1) … (1.4),

- taper ratio $$r = \frac{c_{50}}{c_0};\qquad(1.1)$$
- aspect ratio $$\lambda = \frac{b^2}{S_{ar}};\qquad(1.2)$$
- slenderness factor $$A = \frac{c_0}{b};\qquad(1.3)$$
- shape cutting $$E = \frac{\tan(\chi_{100})}{\tan(\chi_0)}.\qquad(1.4)$$

Starting from Fig. 1.1, the variation law of wing chord along the span for the wing having strait edges is:

$$c(y) = c_0\left[1-(1-r)\frac{2y}{b}\right].\qquad(1.5)$$

From Eqs. (1.1) and (1.2), $c_0 = c_{50}/r$ and $b = \sqrt{\lambda S_w}$ are obtained. Thus, it results:

$$c_{50} = Ar\sqrt{\lambda S_w} \quad \text{or} \quad c_{50} = \frac{2rS_{ar}}{\sqrt{\lambda S_w}(r+1)},\qquad(1.6)$$

$$c_0 = \frac{1}{2}\sqrt{\lambda S_w}(\tan\chi_0 + \tan\chi_{100}) + \frac{2rS_w}{\sqrt{\lambda S_w}(r+1)},\qquad(1.7)$$

The chord at insert (embedded) plane of the wing, empennage or aileron is:

$$c_i = \frac{1}{2}\left(\sqrt{\lambda S_w} - D_{\max}\right)(\tan\chi_0 + \tan\chi_{100}) + \frac{2rS_w}{\sqrt{\lambda S_w}(r+1)},\qquad(1.8)$$

where $D_{\max}$ is the maximum diameter of fuselage.

The reduced surface of wing, empennage or ailerons is:

$$S'_w = S_w - \frac{c_0 + c_i}{2}D_{\max},\qquad(1.9)$$

and the corresponding reduced parameters will be obtained for:

$$\lambda = b'^2/S'_w = (b - D_{\max})^2/S'_w,$$

where b'^2 represents the reduced span.

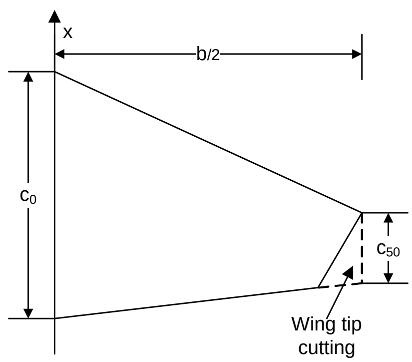


Fig. 1.2. Cutting wing (planform)

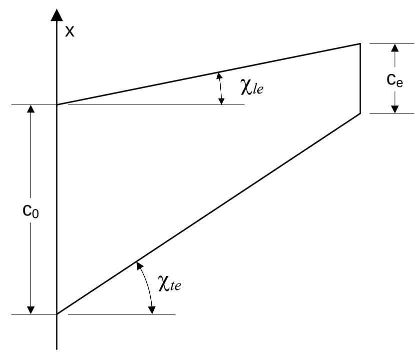


Fig. 1.3. Forward swept wing

The taper ratio r is also an important geometrical parameter connected directly with flight regimes and can vary between 0 and 1 (to avoid indetermination). Thus, in connection with the relative flight speed, for a given Mach number domain, M_{zb}, is referenced:

- $M_{zb} < 0.6$ $\quad r = 1...0.3$;
- $0.6 < M_{zb} < 1.5$ $\quad r = 0.5...0.15$;
- $M_{zb} > 1.5$ $\quad r = 0.2...0$.

In the case of poly-trapezoidal surfaces (made from a certain number of trapezes), the trapezoidal ratio r is maintained:

$$r = \prod_i r_i = \frac{c_{50}}{c_0} \qquad (1.10)$$

where i represents the number of trapezes defined on wing, empennage or/and aileron surface.

The wing aspect ratio λ, as in Eq. (1.2), is another main parameter of wing, empennage and aileron, on whose value its geometric, aerodynamics and mechanical characteristics strongly depend. For a trapezoidal wing, taking into account Eqs. (1.1), (1.2) and (1.3), it is obtained:

$$\lambda = \frac{2b}{c_0}\frac{1}{1+r} \quad \text{or} \quad \lambda = \frac{2}{A}\frac{1}{1+r}. \qquad (1.11)$$

Obviously, for a given form of the wing in plane, the increase of aspect ratio is directly correlated with wing span and conducts to very important consequences on wing, empennage or aileron mechanical behavior, including the answer to creeping (flow), eigenrotation etc.

For missiles in airplane configuration (wings missiles), having low trajectory and subsonic - transonic flight regime, λ = 1.2...2.5 (*small aspect ratio wings*), and they tend to reach λ = 0.5...1 especially for supersonic flight.

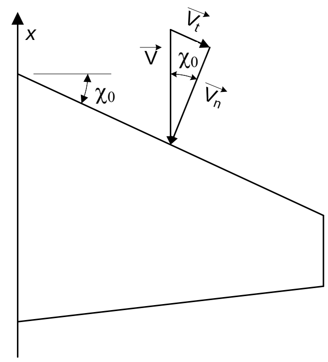


Fig. 1.4. Critical speed derivation

The element which determines the orientation in plane of wing, empennage or aileron of naval missile is sweepback angle χ, measured between the perpendicular line on longitudinal axis of missile and a principal line considered in a given point (one of the edges, the line of maximum thickness, the line of zero momentum, the line of half-chord or quarter of chord etc.). Usually, the reference definition of sweepback angle is between the perpendicular line on longitudinal axis of the naval missile and one of edges (see Fig. 1.1, 1.3). Recommended values are in the domain 0^o … 20^o for subsonic incompressible regime and 20^o … 40^o for subsonic compressible and transonic flight regimes.

For subsonic compressible and transonic flight regimes, the wing with sweepback angle represents an effective way to delay the detachments induces by the shock waves on wing, in boundary layer and in air flow (the cases of appearance of disturbances phenomena, turbulence, vortices, boundary layer detachment and increase of friction). This is the way to obtain a much better behavior of the wing and an appreciable delay of the moment of appearance of critical speed corresponding to critical Mach number, $M_{cr,}$ and normal component of speed, $\overrightarrow{V_n}$.

In accordance with Fig. 1.4, one can write:

$$M_{cr} = \frac{\left(M_{cr}\right)_{\chi=0}}{\cos(\chi)} \qquad \text{or} \qquad \chi_0 = a\cos\left[\frac{\left(M_{cr}\right)_{\chi=0}}{M_\infty}\right]. \tag{1.12}$$

In the case of missiles having supersonic flight, the wing, empennages or ailerons with sweepback angle with rounding front edge, for $M < 1/\cos(\chi_0)$ assure the reduction of drag force. But, χ_0 must not exceed the value $70^\circ 31' 43''$, because it is necessary to maintain a sufficient minim surface of the wing.

3. A new general method for calculating the sweepback angle of wing

In this paragraph, it is presented a new method for determination of sweepback angles of wings, empennages or ailerons edges starting from the position of supersonic flow on aerodynamic profiles for subsonic compressible or transonic flight speed, for some symmetric profiles NACA type (0006, 0009, 63-006, 63-009, 64-006, 64-009, 65-006, 65-009, 65-009, 65-00t6, 65-009). Analysis is made taking into account the determinations presented in NACA Report No. 824 – Summary of Airfoil Data [13] and a comparison of efficiency of profiles adapted to high speed of flight is presented.

Starting from some simple geometric relations, for $r = c_e / c_0$, $0 \le r \le 1$, the following relations occur between sweepback angles of wings, χ_0, χ_{100} and $\chi_{\varepsilon \max}$, considering the speed positions as in fig. 1.5, on maxim thickness:

$$\tan(\chi_0) + \tan(\chi_{100}) = 2\frac{c_0}{b}(1-r); \tag{1.13}$$

$$\tan(\chi_0) + \tan(\chi_{100}) = 4\frac{S_w}{b^2}\frac{1-r}{1+r}; \tag{1.14}$$

$$\tan(\chi_0) + \tan(\chi_{100}) = \frac{4}{\lambda}\frac{1-r}{1+r}. \tag{1.15}$$

Because the analyzed profiles do not have the same coordinate of maximum thickness, $x_{\varepsilon \max}$, the sweepback angle as a function of those of line of maximum thickness, $\chi_{\varepsilon \max}$, determined for M_{cr}, is:

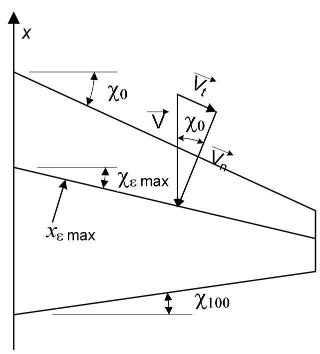


Fig. 1.5. The derivation method

$$\chi_0 = \arctan\left[\tan(\chi_{\varepsilon \max}) - 2\frac{c_0}{b}(1-r)x_{\varepsilon \max}\right]; \tag{1.16}$$

$$\chi_0 = \arctan\left[\tan(\chi_{\varepsilon \max}) - 4\frac{S_w}{b^2}\frac{1-r}{1+r}x_{\varepsilon \max}\right]; \tag{1.17}$$

$$\chi_0 = \arctan\left[\tan(\chi_{\varepsilon \max}) - \frac{4}{\lambda}\frac{1-r}{1+r}x_{\varepsilon \max}\right], \tag{1.18}$$

respective,

$$\chi_{100} = \arctan\left[2\frac{c_0}{b}(1-r)\left(1+x_{\varepsilon\max}\right)-\tan\left(\chi_{\varepsilon\max}\right)\right]; \qquad (1.19)$$

$$\chi_{100} = \arctan\left[4\frac{S_w}{b^2}\frac{1-r}{1+r}\left(1+x_{\varepsilon\max}\right)-\tan\left(\chi_{\varepsilon\max}\right)\right]; \qquad (1.20)$$

$$\chi_{100} = \arctan\left[\frac{4}{\lambda}\frac{1-r}{1+r}\left(1+x_{\varepsilon\max}\right)-\tan\left(\chi_{\varepsilon\max}\right)\right]. \qquad (1.21)$$

But, to establish the optimum value of sweepback angle must one takes into account the fact that simultaneously with its rise the slope of lift curve decreases and this fact has important consequences on rise the missile to flight altitude and soaring to target. Considerations of advantages and disadvantages of sweptback wing must be analyzed in correlation with relative thickness, aspect ratio, wing charge and taper ratio. So, the choice of sweepback angle is a complex problem and very important one because of great implications on flight performances and quality of missile.

Because the angles χ_0 and χ_{100} are connected with the flow speed on wing profile and along the wing, they become dependent on profile thickness. For some classic NACA symmetric profiles, which are characteristic for naval missile wings, for r = 0.146, $\lambda = 1.185$, and $M_\infty = 0.94$ are obtained the results in Table 1 from Eqs. (1.16) … (1.21).

Table 1.

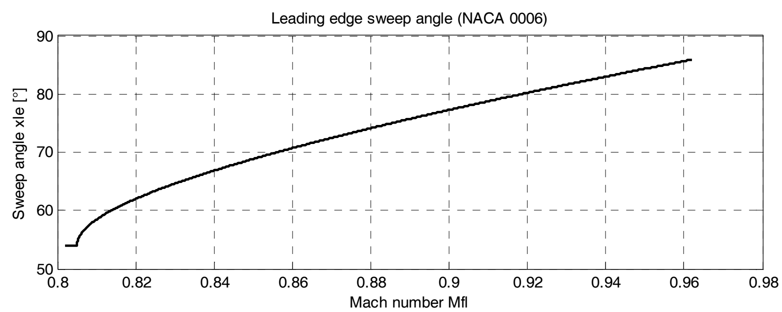
Critical characteristics of analyzed profiles

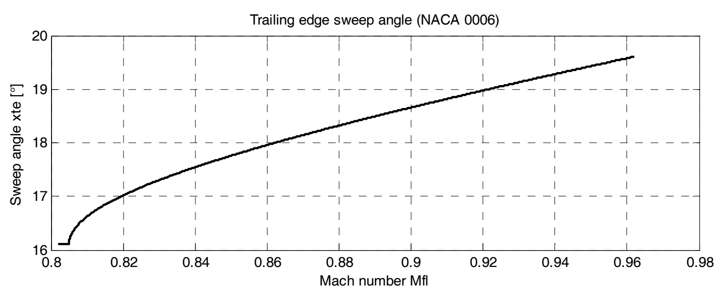
Profile	M_{cr}	χ_0 [°]	χ_{100} [°]
0006	0.805	57.75	13.71
0009	0.766	60.01	13.25
63-006	0.834	57.97	13.67
63-009	0.780	61.02	13.04
64-006	0.836	59.03	13.45
64-009	0.785	61.76	12.87
65-006	0.838	60.02	13.25
65-009	0.790	62.47	12.71
66-006	0.840	61.30	12.79
66-009	0.795	63.43	12.49

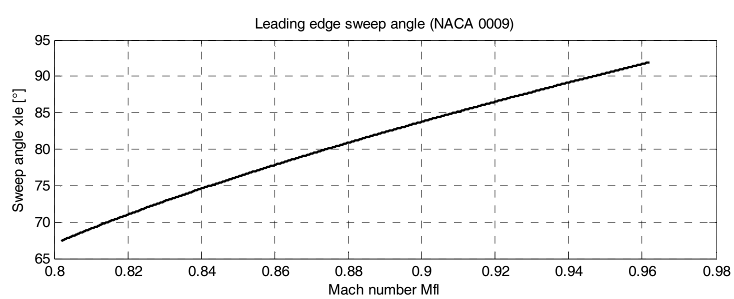
The variations of sweepback angles of wings, empennages and ailerons of naval missiles are presented for an aerodynamic surface having r = 0.146 and characteristics of profiles taken from literature.

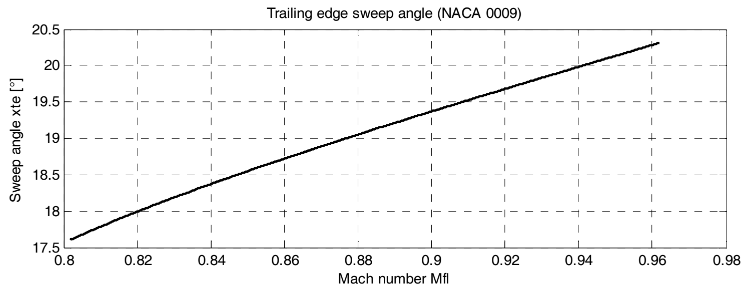
It is seen that the thick profiles (profiles having relative thickness of 6%) are "somewhat indifferent" in first speed domain. The variation of sweepback of leading edge is almost constant until approximately M = 0.8. For greater Mach numbers a rapid increase of sweepback angle of leading edge appears, followed by an almost linear rise of the angle for the relative speed regime which remains. This is the explanation of the fact that critical Mach number of these profiles is placed in the domain 0.805 – 0.840.

Also, results that the NACA profiles 0006 and 0009 asses limits in use for relative speed over $M = 0.86$.








Trailing edge sweep angle (NACA 0009)
Sweep angle xte [°]
20.5
20
19.5
19
18.5
18
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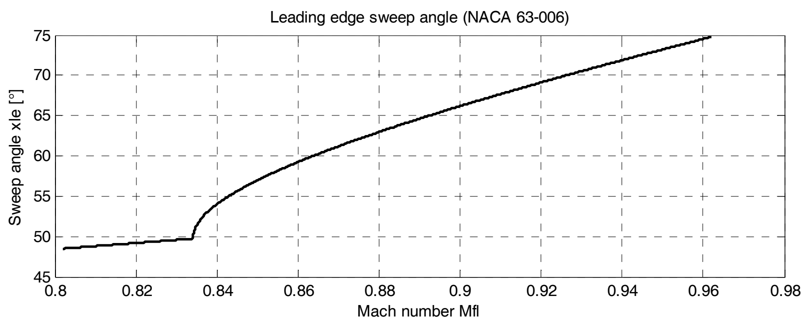
Leading edge sweep angle (NACA 63-006)
Sweep angle xle [°]
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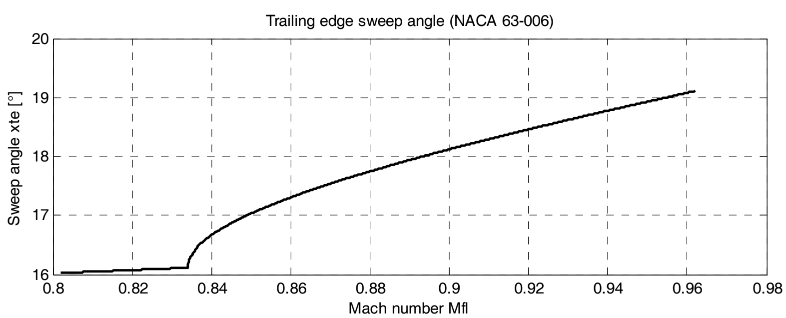
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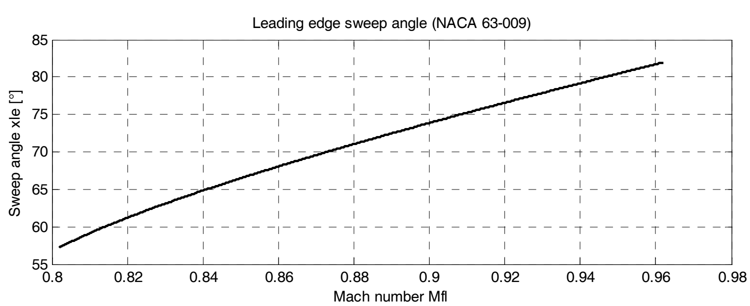
Leading edge sweep angle (NACA 63-009)
Sweep angle xle [°]
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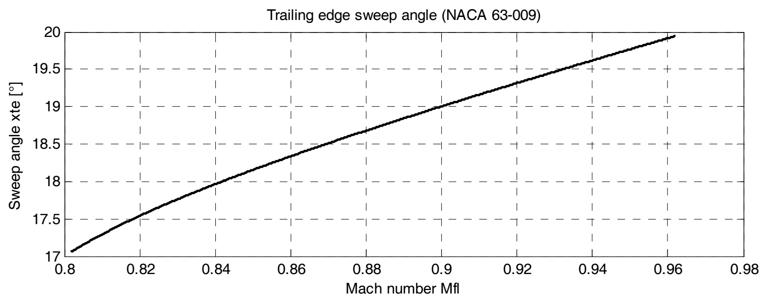
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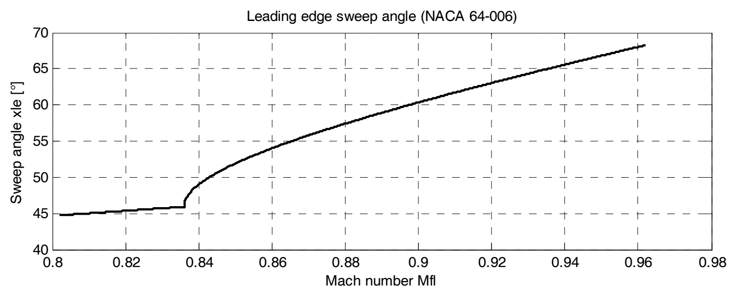
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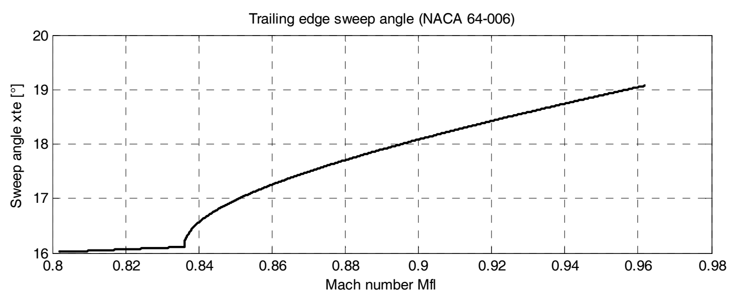
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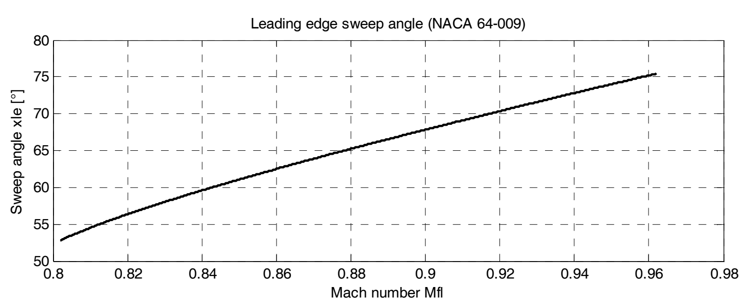
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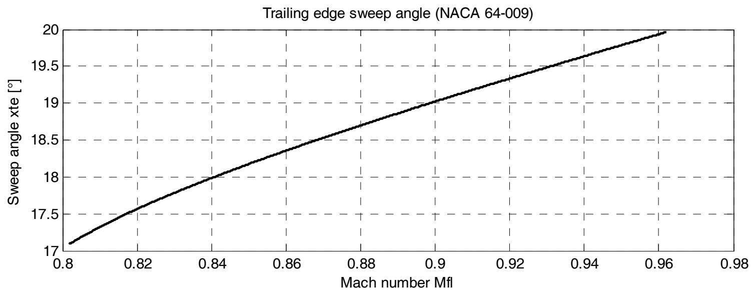
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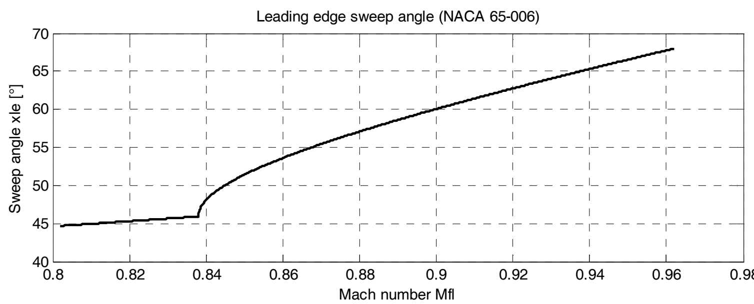
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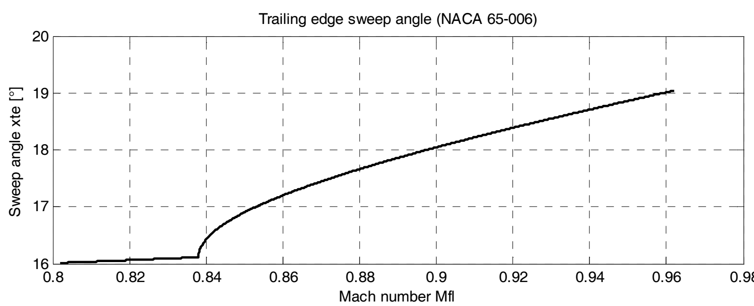
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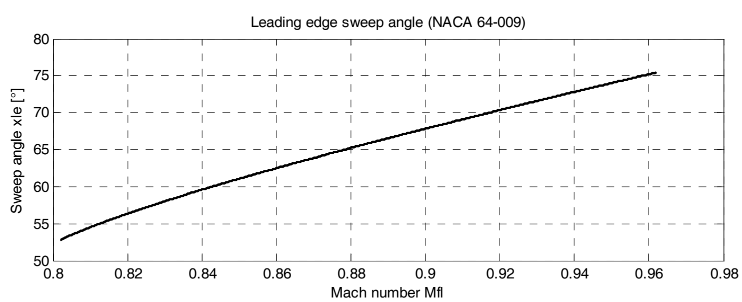
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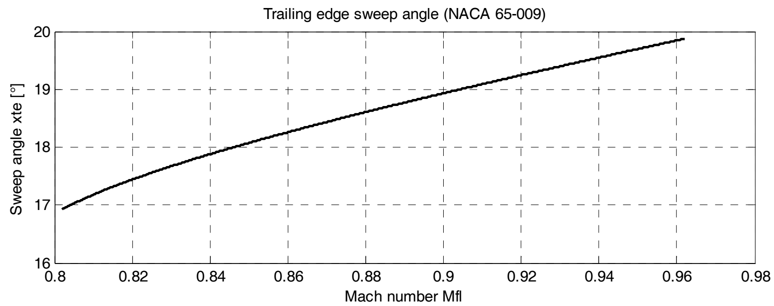
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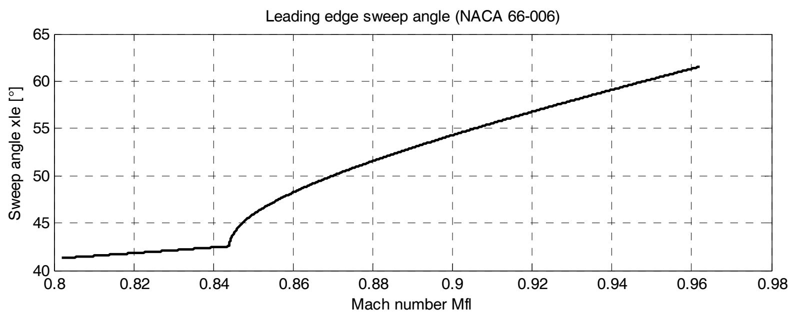
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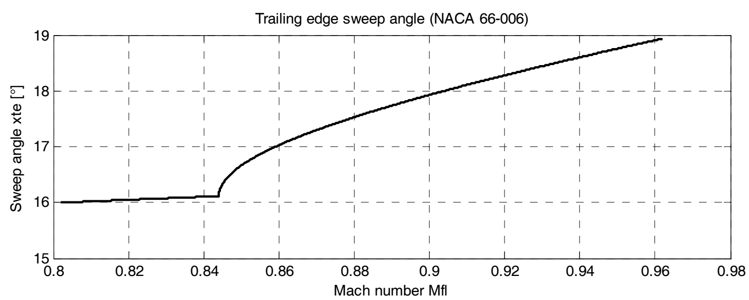
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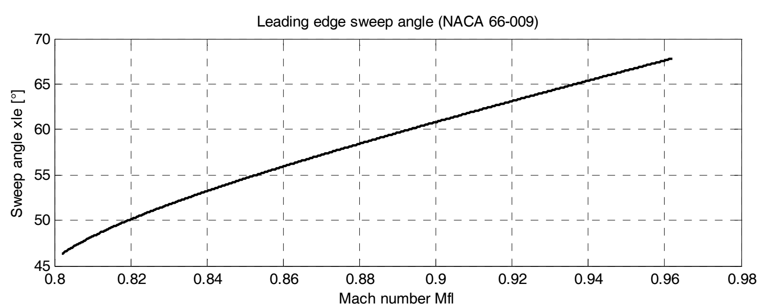
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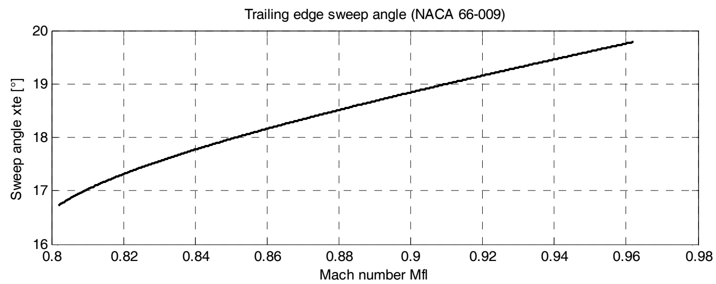

The profiles having relative thickness of 9% are “more sensitive” because the values of critical Mach number are placed in the domain 0.766 – 0.795. So, the variation of sweepback angles of the aerodynamic surfaces edges appears since the beginning of the (flight) domain considered for calculus.

But, taking into account that the shock-waves start to form and to manifest for the same relative flight speed, their influence is more evident in the case of these profiles.

The critical Mach number continues to diminish when the relative thickness of the profiles rises, but profiles having greater relative thickness are not used for wings, empennages and/or ailerons of naval rockets.

Starting from the presented research until now, it is evident that simultaneously with diminishing the values of critical Mach number the influence of the drag force increases due to of earlier appearance of supersonic flow on wings, empennages and/or ailerons surfaces.

Also, it is revealed an accentuated increase of sweepback angles in comparison with the results presented in references about aircraft design for flight speed specific to the naval missiles which operate until now.

As a first conclusion one should underline that the profiles with small thickness are very useful for design and construction of wings, empennages or ailerons of naval missiles, and those having greater thickness are useful for construction of apices or shock wave breakers.

4. Conclusions

Eqs. (1.16) … (1.22) represent a new point of view on calculation of wings for naval missile which differs from those in references.

The variation of sweepback angles for thick profiles, with relative thickness of 6%, is relatively small until M = 0.8. But, beyond this value of Mach number appears a rapid increase of sweepback angle of leading edge, followed by an almost linear increase of the value of this angle in the last part of speed domain. Also, it is seen that the profiles NACA 0006 and 0009 asses limitations for their use for a relative speed over M = 0.86.

For the profiles having a relative thickness of 9%, the variation of sweepback angle of the edges of aerodynamic surfaces begin to manifest starting from values under $M = 0.8$, and the influence is much more evident for these profiles. Also it can be observed an increase of these angles more accentuated in comparison with references data for design of airplanes, for speeds specific to actual operational naval missiles.

As a general conclusion it appears that the thick profiles are useful for wings, empennages and ailerons, and those with greater thickness are useful for apices and shock wave breakers.

The values of sweepback angles presented in Tab. 1 are confirmed (verified) by the real models of naval missiles, and sweepback angle of leading edge can reach a limiting value of 70°31′43″, which is characteristic for subsonic flight speed.

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