AXISYMMETRIC FRONTAL SUPERSONIC INLET FOR TRISONIC AIRCRAFT

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Abstract: *The paper deals with an air inlet meant to equip a trisonic aircraft. Starting from the shock-wave system geometry (two external waves and two internal waves), one has applied an algorithm based on inlet's efficiency maximization, for the most employed flight regime, in order to determine its optimal architecture (optimal angles for the centerbody and the cowl's lip), as well as its characteristic maps. In order to assure a better adapting to aircraft flight regime, one has determined inlets centerbody positioning with respect to the flight Mach number, which may be used as inlet's control law. The study is useful for further inlet's automation possibilities analysis, as well as for similar inlets architecture establishing.*

Keywords: *supersonic, inlet, shock-wave, centerbody, cowl, Mach number, geometry.*

1. INTRODUCTION

One of the most important nowadays challenge for aerospace engineers and manufacturers is the flight at very high speeds, both for military and for civil purposes, for atmospheric and for suborbital and orbital missions.

The interest shown by the military in hypersonic flight is obvious, high speed weapons (or platform for weapons) offering strategic and tactical advantages. Nevertheless, the supersonic and even the hypersonic passenger transport has been reconsidered in the last decade and is still a hot subject up for debates.

Regardless the mission of a high-speed vehicle, a lot of challenges need to be overcome before it could be put into service and fulfill its tasks. The aerodynamic viscous friction effect and the occurred shock waves give so high body temperatures that no conventional materials can withstand them, so new heat-resistant and resilient materials are to be designed and new suitable manufacturing concepts and techniques are to be implemented; aircraft new body structures and new aircraft propulsion systems means new flight techniques, which, obviously, need new sensors, new equipment and suitable commands and control laws and architectures.

High speed aircraft must have suitable propulsion systems (usually air-breathing engines, but also rocket engines), such as high thrust jet engines without or with afterburning, ramjets or scramjets, or even detonation engines (pulse detonation engines, rotating detonation engines or continuous detonation engines). No matter the air-breathing engine, it should have an inlet with suitable geometry, assisted by a control system, in order to assure the necessary air mass flow rate, velocity and pressure and to keep the engine in a stable operating mode ([2, 5]).

Inlets are built up in a variety of shapes and sizes, usually imposed by the speed of the aircraft. The inlet has a very important connection and correlation role; it should transform the air parameters outside the engine into suitable parameters inside the engine, especially when it's about the speed and the pressure.

Improper air velocity in front of the compressor may trigger shock-waves and makes impossible the air compression, while improper pressure condition can lead to a significant thrust decrease, without mentioning the thermal overload. Consequently, the inlet should adapt to the flight regime (reflected by the flight Mach number) in order to keep the pressure and temperature parameters within the permissible range ([2, 5, 6]).

In this paper one has studied an axisymmetric supersonic frontal inlet with mixed compression, meant to equip a trisonic aircraft; the considered flight speed (the freestream air velocity) is at least three times the sound speed $\left(M_H = 3.0\right)$.

2. INLET PRESENTATION

The inlet (see Fig. 1) consists of an axisymmetrical air intake with sharp cowl lip and a conical centerbody (nose). The centerbody triggers two conical shock-waves (which are the source of the external compression), while the intake's cowl lip triggers another conical shock-wave. The last shock-wave is a normal-one and is triggered inside the inlet's duct; the normal shock-wave, together with the lip's conical shock-wave are the source of the internal compression. Consequently, the described inlet is a mixed-compression-one.

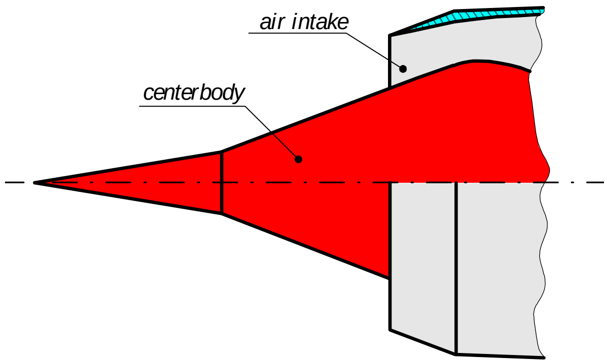


FIG. 1. Supersonic axisymmetric air inlet

The centerbody has two sections, each one having its own flaring angle (θ_1 and θ_2, see Fig. 2); sections' lengths and flaring angles are determined in order to assure the focal point F attachment to the cowl's lip (D-point). Intake's cowl lip has its own angle θ_3 and triggers another conical shock-wave (DC in Fig. 2), which develops inside the intake; together with this conical wave, it appears the final normal shock-wave (CC$^{/}$ in Fig. 2), so the air stream in front of the engine becomes subsonic.

Inlet's characteristics are: a) the efficiency characteristic (which means inlet's total pressure recovery σ_i^* versus freestream Mach number) and b) the flow characteristic (inlet's flow ratio coefficient C_D versus freestream Mach number).

This kind of axisymmetric inlet might be used as frontal inlet (in the front of aircraft's fuselage) for single engine aircrafts or in the front of the nacelle for multi-engine aircrafts (when the nacelles are mounted on the wings or on the fuselage).

The adapting of the inlet to different flight regimes may be realized only by the centerbody's longitudinal displacement (in order to keep the focal point of the external compression outside the intake and avoid the shock-wave reflection inside it).

3. INLET OPTIMAL ARCHITECTURE

Air inlet design is an important engineering issue, involving geometric, aerodynamic and energetic grounds. Inlet's architecture (geometry) design is based on various methods. The aerodynamic methods are based on analytical and numerical procedures, while the geometric methods are based on planar geometry elements. Optimization criteria are, in most of studied cases, the total pressure recovery maximization (Oswatitsch condition), the drag minimization and/or the inlet flow rate correlation; studies are using various methods, such as "carpet search method" (described in [6] and [8]), or the "method-of-characteristics" (presented in [2]).

In fact, the optimal configuration determination consists of centerbody's angles calculus, as well as dimensionless geometry issuing, based on the determined centerbody's angles. Similar algorithms, but for 2D (planar) inlets, were presented and applied in [7, 9, 12, 13], while algorithms for 3D inlets' optimal configurations were described in [3, 9].

3.1. Optimization criteria. As optimization criterion one has chosen the total pressure recovery σ_i^* maximization. Inlet's total pressure recovery (also known as inlet's perfection coefficient, or inlet's total pressure loss coeficient) σ_i^* is given by

$$\sigma_i^* = \sigma_{csw1}^* \sigma_{csw2}^* \sigma_{csw3}^* \sigma_{nsw}^* \sigma_d^* , \tag{1}$$

where σ_{csw1}^*, σ_{csw2}^* are total pressure ratios for the oblique shock-waves triggered by the centerbody, $\sigma_{csw3}^* -$ total pressure ratio for the oblique shock-waves triggered by the cowl lip, σ_{nsw}^* – total pressure ratio for the normal shock-wave and σ_d^* – total pressure ratio into intake's duct (assumed as constant, no matter the flight regime or the engine regime would be).

3.2. Conical shock-wave parameters. Air compression through a conical shock-wave is a little different than through an oblique shock-wave [2, 5, 6, 8]; however, there are a lot of geometric and aerodynamic similarities. Conical shock-wave geometry (see Fig. 3) and behavior are described by Taylor-Maccol equations [2, 5, 6].

The first and the most important issue is the calculation of shock-wave's angle β, with respect to the freestream Mach number M_1 (in front of the wave) and the cone angle θ_c. It might be calculated using an implicit non-linear equation (presented in [2] and in [5]):

$$\sin^2\beta = \frac{1}{M_1^2}\frac{1.2}{\cos\beta}\left(\frac{1}{\cos\beta} - \frac{1}{\cos\theta_c} + \ln\frac{\mathrm{tg}\frac{\beta}{2}}{\mathrm{tg}\frac{\theta_c}{2}}\right)^{-1} , \tag{2}$$

while the other parameters may be calculated very similar to the oblique shock-wave. Thus, the

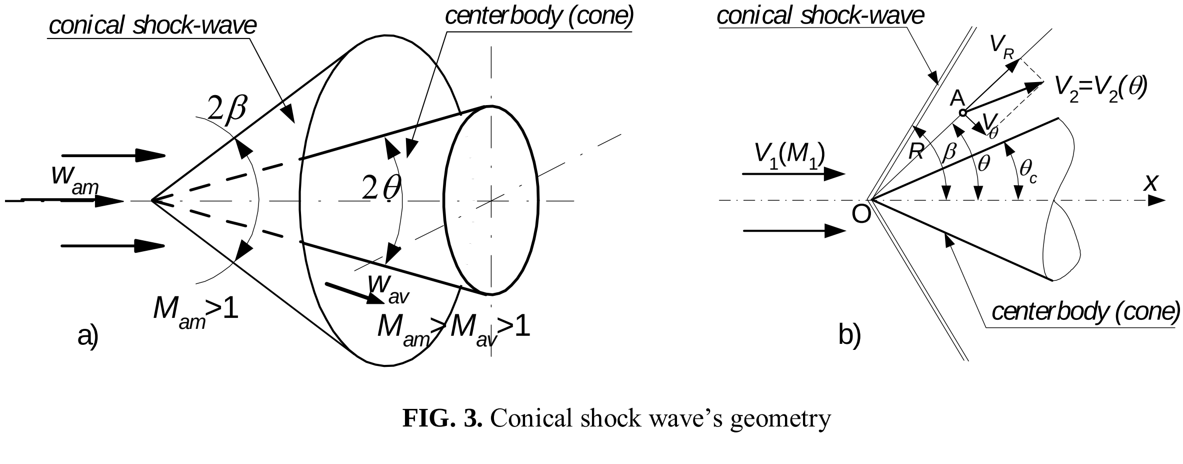


FIG. 3. Conical shock wave's geometry

normal Mach number in the front of the wave M_{1n} is

$$M_{1n} = M_1 \sin\beta, \tag{3}$$

while the normal Mach number behind the wave M_{2n} is similar to the oblique shock-wave:

$$M_{2n} = \sqrt{\left(0.4M_{1n}^2 + 2\right)\cdot\left(2.8M_{1n}^2 - 0.4\right)^{-1}}; \tag{4}$$

the tangent Mach number value remains the same before and behind the shock-wave , $M_{2t} = M_{1t}$:

$$M_{2t} = M_{1t} = M_1 \cos\beta, \tag{5}$$

so the Mach number behind the wave becomes

$$M_2 = \sqrt{M_{2n}^2 + M_{2t}^2}; \tag{6}$$

this Mach number will be the front Mach number for the next shock-wave.

Total pressure recovery coefficient becomes

$$\sigma_{csw}^* = \left[\frac{2.4M_{1n}^2}{2 + 0.4M_{1n}^2}\right]^{3.5}\left[\frac{2.4}{2.8M_{1n}^2 - 0.4}\right]^{2.5}, \tag{7}$$

which, obviously, depends on the values β and θ_c as long as $M_{1n} = M_1(\beta, \theta_c)$.

3.3. **Determining of inlet's optimal geometry.** As stated in [5, 8], inlet's design is performed considering as "nominal" the most intense and most used flight regime. As long as the inlet is a frontal-one and the aircraft it equips can reach a cruise flight speed more than three times the speed of sound, which corresponds to a Mach number bigger than 3, this one will be considered as the nominal Mach number; so, for the geometrical optimization, one has to use the freestream Mach number $M_H = 3.3$ as the M_1 Mach number in front of the inlet.

The optimal inlet configuration is given by the situation when all of the conical shock-waves are convergent into the cowl lip, as Fig. 4 shows; that means that the focal point (point F in Fig. 2) overlaps the cowl lip (point D in Fig. 2).

As far as centerbody's flares angles were chosen as equal $(\theta_1 = \theta_2 = \theta)$, while cowl's lip angle was chosen as half value $(\theta_3 = 0.5 \times \theta)$, the algorithm of optimization must determine the value of θ which assures the maximum value of total pressure recovery coefficient σ_i^*.

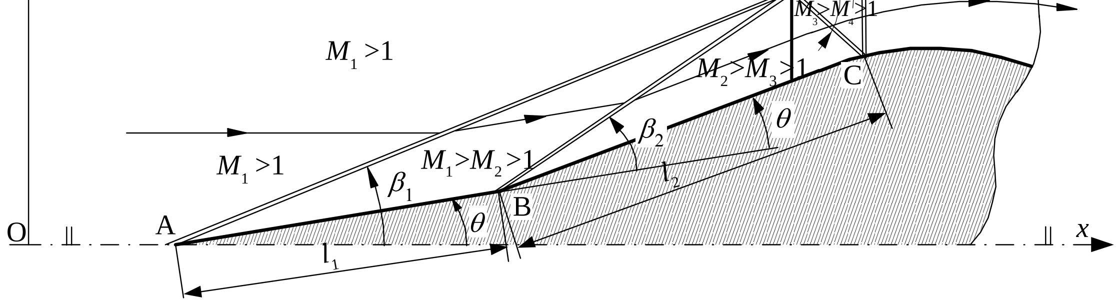


FIG. 4. Inlet with optimal geometry operating at the nominal flight regime

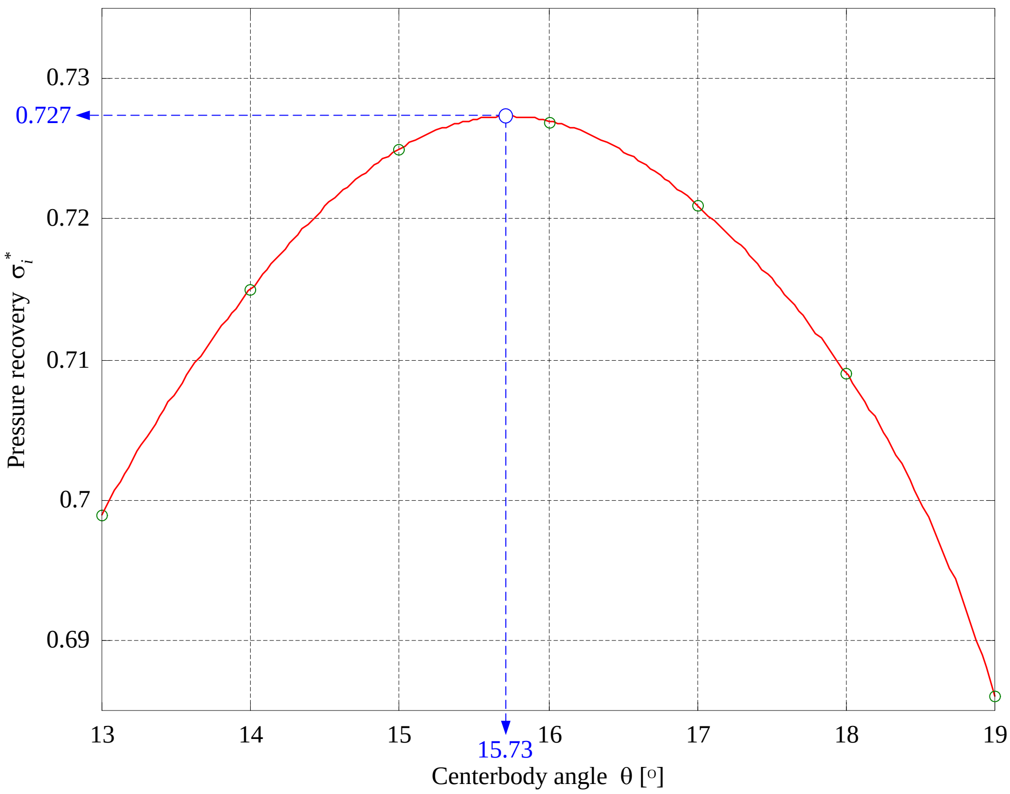


FIG. 5. Total pressure recovery coefficient versus the centerbody angle

Therefore, one has to choose a number of n values for θ and for each configuration (given by a value $\theta_k\left(k=\overline{1,n}\right)$ of the current angle) one has to use the equations (2) to (7) for each one of the conical shock-waves (two external and one internal), in order to determine their total pressure recovery coefficients and the Mach number behind these waves; the last shock-wave is the normal-one, but Eq. (7) may be used for total pressure recovery coefficient calculation; finally, using Eq. (1), the overall inlet total pressure recovery coefficient will be determined.

Applying the algorithm for each $\theta_k\left(k=\overline{1,n}\right)$, one obtains the pressure recovery coefficients $\left(\sigma_i^*\right)_k, k=\overline{1,n}$; the dependence σ_i^* versus θ is graphically represented in Fig. 5. The curve $\sigma_i^*(\theta)$ is a parabolic-one with a maximum point, which corresponds to the maximum possible pressure recovery value $\left(\sigma_i^*\right)_{\max}=0.727$; it is given by the optimal θ – value of the centerbody's flares and of the cowl lip, which is $\theta_{\mathrm{opt}}=15.73^{\circ}$.

As stated in [5, 8], the value of the flare angle should be chosen smaller than θ_{opt} with $0.5^{\circ}\div 2.0^{\circ}$, in order to avoid that the conical shock-waves (triggered by the centerbody) disengage too soon at low supersonic flight speeds. Consequently, one has to choose as centerbody's flare angles the value $\theta_1=\theta_2=15^{\circ}$.

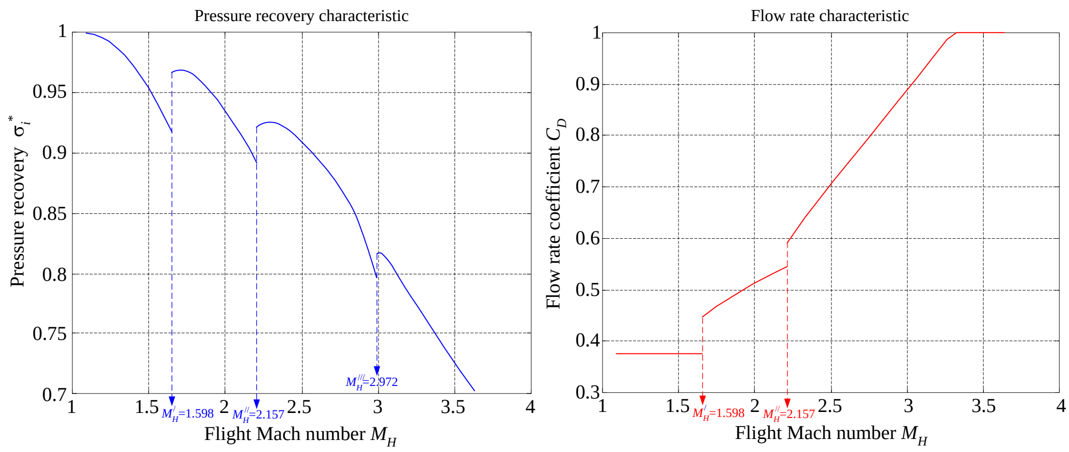
Based on these flare angle values, by solving a simple analytical geometry problem, one can obtain the dimensionless inlet geometry (as shown in Fig. 4), considering the D-point coordinate as equal to the unit $\left(y_{\mathrm{D}}=1\right)$ and the nominal mach number $M_H=3.3$; consequently, after determining β_1, β_2 and β_3 angles (by solving Eq. (2) for each conical external and internal shock-wave), the coordinates of the important nodal points in Fig. 4 become, as follows: A (0;0); B (1.186; 0.329); C (1.983; 0.831); C$'$ (1.983; 1.103); D (1.678; 1), while the lengths of the segments AB and BC are $l_1=1.231$, $l_2=0.942$.

4. INLET BEHAVIOR VERSUS FLIGHT REGIME

The optimal inlet architecture was designed for a nominal Mach number $M_H = 3.3$, but during the flight, different flight Mach numbers may occur. For different $M_1^{/}$ flight Mach numbers, $M_1^{/} < M_{1_{\text{nom}}} = 3.3$, external and internal conical shock-waves are depleting, (as in Fig. 2, comparing to Fig. 4), so angles β_1, β_2 and β_3 are growing, which means that σ_i^* modifies too; withal, the cross section area A_H of the air-breath stream also diminishes.

4.1. Inlet's pressure recovery characteristic chart. As long as the flight Mach number modifies, the shock-waves' geometry and parameters are modifying too, as follows: $\beta_1^{/} = \beta_1^{/}\left(M_1^{/}, \theta\right)$, $M_2^{/} = M_2^{/}\left(M_1^{/}, \theta\right)$, $\beta_2^{/} = \beta_2^{/}\left(M_2^{/}, \theta\right)$, $M_3^{/} = M_3^{/}\left(M_2^{/}, \theta\right)$, $\beta_3^{/} = \beta_3^{/}\left(M_3^{/}, \theta/2\right)$, $M_4^{/} = M_4^{/}\left(M_3^{/}, \theta/2\right)$, $M_5^{/} = M_5^{/}\left(M_4^{/}\right)$, as Eqs. (2) to (6) shows; consequently, each one of the pressure recovery coefficients' values (given by Eq. (7)) changes $\sigma_{csw_k}^* = \sigma_{csw_k}^*\left(M_k^{/}, \beta_k\right), k = \overline{1,3}$, $\sigma_{nsw}^* = \sigma_{nsw}^*\left(M_4^{/}\right)$ with respect to the flight regime Mach number value and, finally, one obtains a dependence $\sigma_i^* = \sigma_i^*\left(M_1^{/}\right)$, which is the pressure recovery characteristic (also known as *pressure characteristic* or as *flight characteristic*).

The above-mentioned characteristic chart is graphically presented in Fig. 6.a); it is noteworthy that the pressure recovery characteristic is not a continuous curve, but it has three discontinuity points, corresponding to some occurred phenomena, such as shock-wave detaching. Thus, considering a decreasing flight Mach number, the first discontinuity point corresponds to $M_H^{///} = 2.972$ when the internal normal shock-wave disappears and the internal conical shock-wave becomes a normal shock-wave in front of the cowl lip; the second discontinuity point corresponds to $M_H^{//} = 2.157$, when the third shock-wave has disappeared and the second external conical shock-wave detaches and becomes a normal shock-wave; the third discontinuity point corresponds to $M_H^{/} = 1.598$, when the first external conical shock-wave detaches and becomes a normal shock-wave just in front of the centerbody and the whole inlet operates like a subsonic-one, because the whole freestream in front of the inlet has subsonic velocity.



a) Inlet pressure recovery characteristic map b) Inlet flow rate characteristic map

FIG. 6. Inlet's characteristic maps (fixed geometry architecture)

4.2. Inlet flow rate characteristic chart. Flow rate coefficient, noted as C_D, is defined as the ratio of the current flow rate and the nominal flow rate [5]; this definition is equivalent to the one which uses the air-breathing circular cross-section areas ratio $A_H / A_{1'}$, which are given by the co-ordinates y_G and y_D in Fig. 2:

$$C_D = \frac{A_H}{A_{1'}} = \frac{A_H}{\left(A_H\right)_\mathrm{nom}} = \frac{\pi y_\mathrm{G}^2}{\pi y_\mathrm{D}^2} = \frac{y_\mathrm{G}^2}{y_\mathrm{D}^2} = y_\mathrm{G}^2 . \tag{8}$$

Obviously, y_G coordinate depends on the flight Mach number $M_1^{/}$, while y_D coordinate is constant, which means that the flow rate coefficient depends on the flight Mach number $C_D = C_D\left(M_1^{/}\right)$. Flow rate characteristic chart is graphically presented in Fig. 6.b).

Unlike the pressure characteristic, the flow rate characteristic curve has only two points of discontinuity, corresponding to the Mach numbers $M_H^{//} = 2.157$ and $M_H^{/} = 1.598$, very similar to the flow rate characteristic for the planar inlets with external compression (as presented in [1, 12]). In fact, the flow rate is influenced only by the external conical shock-waves positions, which are responsible of the air-breathing tube cross-section diminishing when the inlet's frontal Mach number (the flight Mach number) diminishes.

5. INLET CONTROL LAW

Operation of an inlet with fixed geometry architecture means a lot of losses from air flow rate's point of view, as Fig. 6.b shows; especially for low or medium Mach numbers, the flow coefficient C_D is far from the maximum value and it could lead to buzz behavior of the inlet, especially when the engine's regime decreases.

In order to grow the C_D-value, a suitable solution is to keep the second conical shock-wave attached to the cowl's lip, progressively displacing longitudinally the centerbody, which means that the inlet should be tuned with respect to the flight regime. As Fig. 2 shows, when the flight regime is less intense than the nominal-one, the conical shock-wave are depleting and moving away from the cowl's lip, so the focal point F departs from D. Consequently, in order to bring back at least the second wave on the cowl's lip, the distance DD$^{/}$ should be cancelled; it could be achieved only by retracting the centerbody. On the contrary, if the flight regime becomes more intense than the nominal-one, the centerbody should be pulled out of the intake (the distance DD$^{/}$ has become negative), to keep the shock-waves outside the intake.

As long as the position of D$^{/}$ - point on the shock-wave depends on the waves angle, which, in turn, depends on the flight Mach number, it leads to the dependence of the DD$^{/}$-distance on the flight regime (flight Mach number). Centerbody's displacement with respect to the flight Mach number represents the inlet's control law; its graphical expression being depicted in Fig. 7, where the length x_{cb} represents the distance (measured on the *x*-axis) between the cowl's lip, D-point, and the centerbody's tip, A-point. An alternative control law would be the one which assures the DD$^{/}$-distance cancellation by translating the entire intake's cowl while the centerbody position is kept fixed. In fact, the longitudinal displacement of the centerbody and/or of the intake's cowl are the only means for axisymmetric inlets tuning with respect to the flight regime (Mach number).

As Fig. 7 shows, the control law has three stages:

a) stage I, corresponding to the low supersonic flight speeds, when the flight Mach number is under $M_H^{/} = 1.598$ and the centerbody's tip triggers a detached normal shock-wave.

Centerbody's position is fixed, the distance x_{cb} being constant $\left(x_{cb}=0.172\right)$. In fact, this might be the centerbody's position even for subsonic flights;

b) stage II, corresponding to the medium supersonic flight speeds, when the Mach number is between $M_H^{/}=1.598$ and $M_H^{//}=2.157$. The centerbody's tip triggers the first conical shock-wave, while the centerbody's second conical section triggers a detached normal shock-wave. Just as in the first stage, centerbody's position is fixed, the distance x_{cb} being constant $\left(x_{cb}=1.364\right)$;

c) stage III, corresponding to the high supersonic flight speeds, when the Mach number is bigger than $M_H^{//}=2.157$ and the centerbody triggers both conical shock-waves. The control law is a non-linear-one, described by the polynomial:

$$x_{cb}\left(M_H\right)=0.0816\times M_H^4-0.797\times M_H^3+2.5847\times M_H^2-2.617\times M_H+1.307\,. \tag{9}$$

If one chooses to use the cowl displacement instead the centerbody's displacement as inlet's tuning method, the control law is similar.

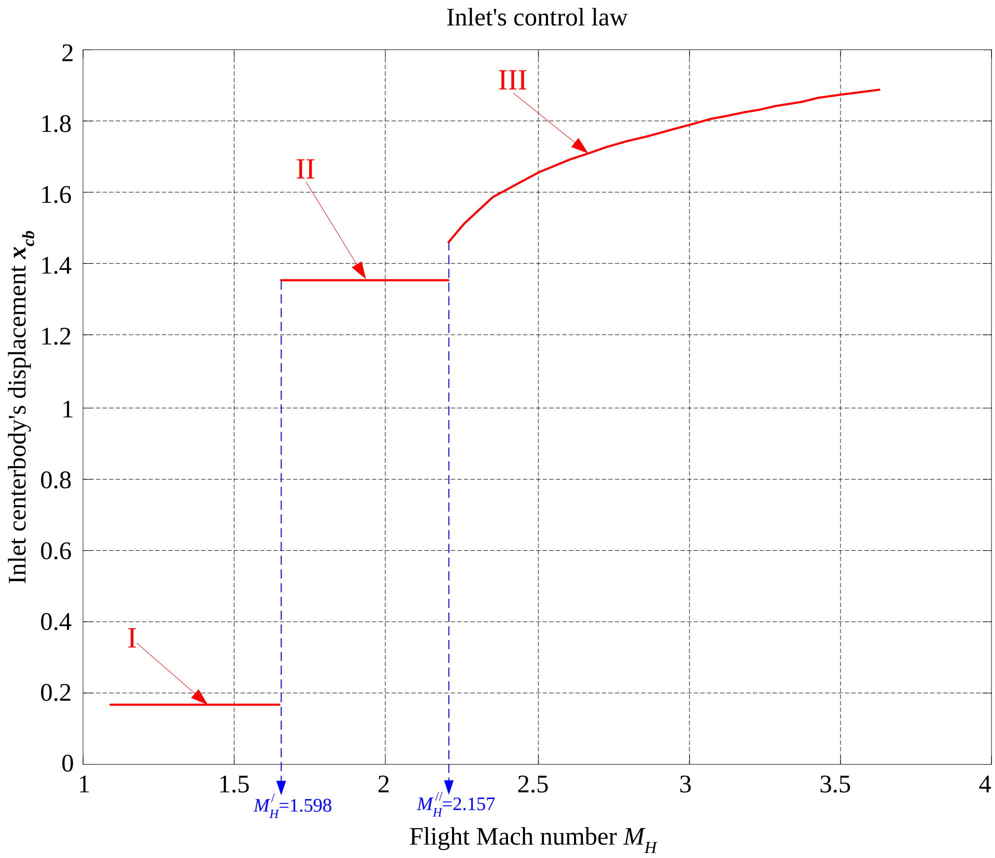


FIG. 7. Inlet's control law (centrbody's displacement)

CONCLUSIONS

Supersonic inlets for aircraft are built in a large range of shapes and sizes, which are usually imposed both by the flight speed of the aircraft and by the position of the inlet on aircraft's airframe. Axisymmetric inlets might be used as frontal inlets: in the front of aircraft's fuselage for single engine aircrafts, or in the front of the nacelle for multi-engine aircrafts (when the nacelles are mounted on the wings or on the fuselage).

Inlet's optimal architecture issuing was made using a supersonic inlet optimization algorithm based on inlet's total pressure recovery coefficient maximization (total pressure of the entire shock-waves system recovery). Main geometric elements of the inlet are: centerbody's flare angles (θ_1 and θ_2), centerbody's panels' lengths (l_1 and l_2), as well as cowl lip's position. All of these elements were determined for a hypothetical fixed geometry inlet, for a nominal frontal Mach number $M_H = 3.3$, the inlet being designed as frontal air intake of a trisonic aircraft.

In order to simplify the architecture, one has chosen the same value θ for both of the flare angles of the centerbody, while the cowl lip's angle was chosen as half of this value. The algorithm applying has as result a graphic dependence of the inlet's pressure recovery coefficient on the θ – value as a curve with maximum value, which gave the optimal value of θ angle. One has chosen the value for the optimal architecture configuration and one has also determined this configuration, consisting of the nodal points coordinates of inlet's scheme.

Based on this configuration one has established the total pressure recovery characteristic, as well as the flow rate characteristic for the studied inlet.

Inlet's control law, consisting of inlet's conical centerbody positioning, with respect to the flight regime, is not a continuous curve (as Fig. 7 shows); it has two discontinuity points, which corresponds to the critical regimes, when the conical shock-waves triggered by the centerbody are to be detached; moreover, it has two flat levels (the first is for low supersonic flight regime, under $M_H^{/}$, the second - for flight regimes between $M_H^{/}$ and $M_H^{//}$), while the third part of the control low is a nonlinear-one, continuously growing with the flight regime.

However, the inlet is sensitive to the engine operating regime's changes too; in fact, engine's regime affects the position of the shock-waves in front of, or inside the intake [5, 8, 10], so other control laws (with respect to aircraft engine's regime) could be issued (as in [10, 11]), but using the same mobile elements (centerbody or intake's cowl), suitable designed in order to assure the desired shape of the internal duct of the air intake.

The paper has studied the architecture and the control law possibilities, but it could be continued with a study concerning possible control systems meant to realize the designed control law(s) and to assure the suitable operation of the inlet.

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