CONTROL LAW FOR AN AIRCRAFT SUPERSONIC AIR INLET WITH INTERNAL COMPRESSION

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Abstract: *This paper deals with a supersonic air inlet Laval-type. Based on thermo- and gas-dynamic phenomena, the authors have determined the possibilities of Laval-type intake starting process; the starting envelope of the intake was also defined and graphically depicted. Some operating regimes of the intake, correlated to engine's operation were studied and intake's adjusting possibilities were described, as intake's work-lines; these lines were depicted on intake's operational envelope and some control law(s) were determined with respect to the work-lines. Possible control architecture may be emphasized.*

Keywords: *intake, Laval, supersonic, starting, control, work line, Mach number.*

1. INTRODUCTION

The air inlet of an aircraft engine is of prime importance; in fact, for all airbreathing propulsion systems the inlet plays a major role. Its major function is to collect the atmospheric air at free stream Mach number, to slow it down (even if a change of flow direction might be involved) and so, to compress it efficiently.

In this matter of issue, aircraft engine's inlet is performing an essential part of its thermodynamic cycle; moreover, inlet's efficiency is connected to the engine's performance, being directly reflected in it. The inlet must supply engine's downstream components with air at suitable velocities and pressures, with an acceptable degree of uniformity, under any flight condition. Nevertheless, the air inlet has to achieve all these tasks with minimum external drag and to assure to the external flow (around aircraft's body and/or nacelle) a minimum disturbance.

Air inlets (or simply intakes) play important roles in the stability and performance of the installed propulsion systems and, as a result, in overall flying vehicle operation. Moreover, supersonic air inlets (for supersonic aircraft) have a crucial importance, since they must satisfy, for all flight conditions, the needs of the engine for sufficient air, obviously with specific properties and requests, such as low pressure-loss (high recovery coefficient) and low value of distortion, running from ground test operation to supersonic flights [8]. Withal, supersonic inlets have complex flow-field; it might occur shock waves and/or expansion waves, shock waves-boundary layer interactions, flow separation, buzz/stall instability etc. That is the reason why inlets' studying involves both experimental and numerical analysis, in order to better understand their internal and external flow-field, as well as to better predict their operational characteristics and behavior during flights at subsonic and at supersonic velocities.

There are several classifications for supersonic intakes based on their characteristics, like geometry or compression mechanism.

The two-dimensional (2D) and axisymmetric CFD analysis of air inlets are conventional respectively for rectangular and axisymmetric/semi-axisymmetric intake, which neglect the 3D effects of flow-field. However, 3D effects, for example due to sidewall and cross flows, particularly in separation and shock-boundary layer interaction regions for all air intake types, are considerable [5, 8, 10, 11, 17].

Supersonic inlets with internal compression are devices that perform dynamic air compression only inside the flow channel, the air velocity in the forward inlet section being supersonic. Some of them uses internal shock-waves for slow down the flow stream (as presented in [2, 12, 13]), but other uses their specific geometry. These inlets have their flow passage of the inward compression intake devices of the form of a Laval nozzle, so they are also called just intakes, or Laval intakes.

This paper intends to study such a Laval intake and to establish possible control law(s), as well as a possible control architecture(s).

2. ABOUT SUPERSONIC LAVAL INTAKES

As presented in Fig.1, the Laval intake operates like a reversed Laval nozzle; from the input inlet section $1^{/}$ to its throat (its minimum section, noted as *"min"*), the channel is convergent, while from the throat to the output section 1 (which is, in fact, the compressor's input section) the channel is divergent.

Under ideal conditions, when the air flow deceleration is rendered isentropically (hence the name of the device) and the boundary layer is absent, in the convergent zone of the flow channel of the device the compression of the supersonic air stream occurs in the form of a system of low intensity pressure waves (as seen in Fig.1). In the minimum section of the channel, the air velocity becomes sonic (equal to the sound speed). Further compressed air, which already has a subsonic speed, takes place in the divergent zone of the flow channel. Therefore, the ideal device with internal compression operates as an inverted Laval nozzle.

Thus, the breathed air tube in front of the device is cylindrical, the cross area of its section being the same in the inlet's input section $1^{/}$ as in any undisturbed upstream sections, generically denoted by *H*. Inside the air intake, in its convergent zone, the air flow decreases continuously its speed, but it still remains supersonic, between the sections $1^{/}$ and *min* where it reaches the sonic speed (which is also the critical section; after it, the air flow converts to a subsonic flow and continuously decelerates as a result of the divergence between the sections *min* and 1. If the air were an inviscid fluid, its evolution would be realized under ideal conditions, without total pressure loss, thus $\sigma^{*}_{DA} = 1$.

Obviously, in the real operation mode, the boundary layer appears on the walls of the channel and its thickness increases spectacularly in the direction of the air flow, inside the flow channel of the Laval intake.

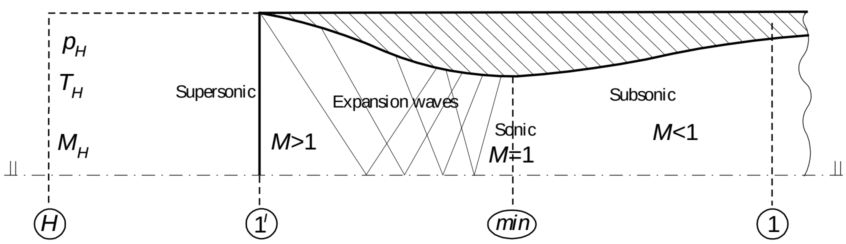

FIG. 1 Supersonic inlet with internal compression of inverted Laval type

If the profiling of the internal flow channel would thus be realized as its walls are generators of oblique shock waves, then, due to the interaction between these waves and the boundary layer, wall flow separations may occur, as well as changes of the flow spectrum compared to the calculation regime situation.

Therefore, in order to maintain the flow pattern corresponding to the compression mode of the internal compression inlets, it is necessary to profile their flow channel so that the flow section area succession to be smooth, without any sudden changes in the geometry of the walls; furthermore, the walls might be provided with holes for the boundary layer sucction, which, overall, is difficult to achieve.

Apart from the difficulties coming from the profiling of the inlet's channel and from the substantial influence of the boundary layer on the flow regime, the practical use of supersonic intakes with internal compression is also difficult because of the difficulty of bringing and stabilizing their operation at a nominal regime, operation generally known as "Starting the inlet". In order to reveal the peculiarities of the starting process, it is necessary to determine the mathematical relations for the calculation of the functional sections areas of the Laval intake.

3. SUPERSONIC INLET'S INTERNAL COMPRESSION STARTING

The mechanism of the internal dynamic compression's starting inside the inversed Laval inlet device must be explained after the classical Laval nozzle starting is studied and explained; this kind of nozzle assures the output of a supersonic flow starting from a subsonic flow input, using only its geometry (its internal flow channel shape).

3.1. Laval nozzle's starting. The starting of the subsonic-supersonic Laval-type nozzle, described in [7,8], calls for the assumption of continuous flow, without friction or heat exchange. It is supposed to be known: the nozzle geometry (A_{cr} and A_e , as well as the cross section area variation along the length of the nozzle $A = A(x)$), the air flow rate $\dot{m}_a$ passing through the nozzle, as well as the parameters of the upstream air (p^* and T^* or i^*), as presented in Fig. 2. Depending on the downward pressure values, there are several flow-related situations, which means several nozzle pressure variation curves.

If the flow rate $\dot{m}_a$ through the nozzle is less than the maximum (critical) flow rate, then the flow velocity is maintained subsonic across the Laval nozzle (curves 1 and 2, Fig. 2).

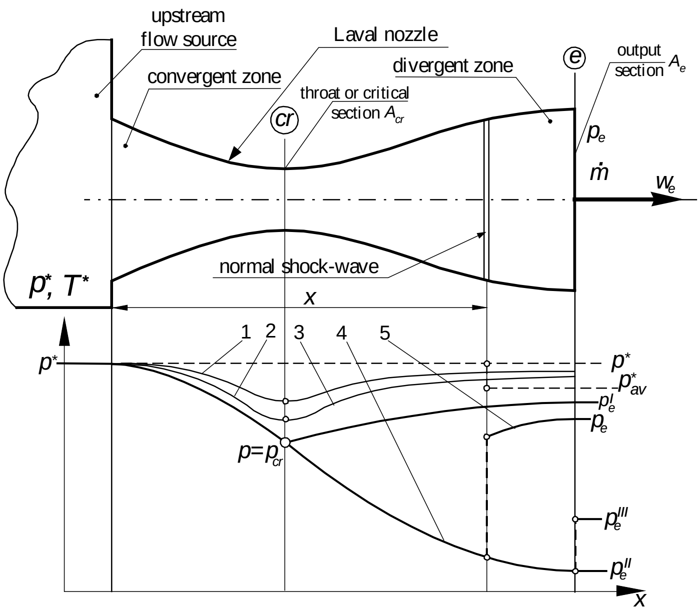

FIG. 2 Laval-type exhaust nozzle starting process [8]

When the maximum flow rate is reached, critical conditions are obtained in the throat, so the convergent portion is considered as primed, but the flow in the divergent zone may be subsonic (curve 3, Fig. 2), or supersonic (curve 4), depending on the downstream effective conditions (that means the static pressure at the nozzle exit p_e).

From the Saint-Venant equation [7], written for both throat and exit section, one obtains

$$\beta_e^{\frac{2}{\chi}}\left(1-\beta_e^{\frac{\chi-1}{\chi}}\right)=\frac{\chi-1}{2}\left(\frac{2}{\chi+1}\right)^{\frac{\chi+1}{\chi-1}}\left(\frac{A_{cr}}{A_e}\right)^2, \tag{1}$$

where $\beta_e=\frac{p_e}{p^*}$ is a value which may be calculated, knowing p_e and p^*. This equation has two roots, one for the subsonic regime $\beta_e^/>\beta_{cr}$, the other for the supersonic regime $\beta_e^/<\beta_{cr}$, where $\beta_{cr}=\left(\frac{2}{\chi+1}\right)^{\frac{\chi}{\chi-1}}$; they correspond to the pressures in the exit section $p_e^/$, respectively $p_e^{//}$.

If the pressure downstream of the nozzle is $p_e \geq p_e^/$, then the flow regime is completely subsonic (curves 1, 2, 3). Curve 3 of Fig. 2 corresponds to the pressure value $p_e^/$ and represents the limit curve of the subsonic flow range across the nozzle. If $p_e<p_e^{//}$, then, the flow regime is supersonic in the divergent zone (curve 4), and the Laval nozzle is completely started.

The situation when $p_e^{//}<p_e<p_e^/$ corresponds to the establishment of a mixed flow regime in the divergent zone, characterized by the occurrence of a normal shock wave within this area. The pressure range may be even more limited if it is considered that the starting of the nozzle is complete when the normal shock-wave occurs in the output section; the velocity coefficient $\lambda_e^{///}$ before the shock-wave, can be determined from the flow rate equation, choosing the supraunit solution $\left(\lambda_e^{///}>1\right)$,

$$q\left(\lambda_e^{///}\right)=\frac{\dot{m}\sqrt{T^*}}{KA_e p^*}, \tag{2}$$

while, behind the shock-wave, the velocity coefficient is $\frac{1}{\lambda_e^{///}}$. The flow rate function is

$$q(\lambda)=\lambda\left[\frac{\chi+1}{2}\left(1-\frac{\chi-1}{\chi+1}\lambda^2\right)\right]^{\frac{1}{\chi-1}}. \tag{3}$$

By the shock-wave the total pressure suffers a loss, so, behind the wave, the pressure will be calculated starting from the same flow conservation equation,

$$p_{av}^*=\frac{\dot{m}\sqrt{T^*}}{KA_e q\left(\frac{1}{\lambda_e^{///}}\right)}, \tag{4}$$

One can also calculate the limit of the external pressure $p_e^{///}$ (the value of the outside pressure below which the Laval nozzle is fully started)

$$p_e^{///} = p_{av}^* \Pi\left(\frac{1}{\lambda_e^{///}}\right) = \left[\dot{m}\sqrt{T^*}\,\Pi\left(\frac{1}{\lambda_e^{///}}\right)\right] / \left[KA_e q\left(\frac{1}{\lambda_e^{///}}\right)\right], \tag{5}$$

where $\Pi(\lambda) = 1 - \frac{\chi - 1}{\chi + 1}\lambda^2$ is the thermodynamic funcion of the pressure.

Consequently, it can be concluded that the following situations may occur during the Laval nozzle starting, depending on the value p_e of the static pressure downstream of the nozzle:

a) if $p_e \geq p_e^{/}$ the nozzle is totally under subsonic flow;

b) if $p_e^{/} > p_e > p_e^{///}$ the nozzle shows a mixed flow in its divergent zone, being triggered a shock-wave; the upstream flow is supersonic, re-becoming subsonic downstream (curve 5, in Fig. 2);

c) if $p_e < p_e^{///}$, the shock-wave is completely discharged from the nozzle, and this one is fully primed (started).

One of the most importnt problems to be studied in the case of the emergence of a shock-wave in the nozzle's divergent zone is the determination of its position, with respect to the critical section or to the nozzle entry section, under the conditions of knowledge of the upstream $\left(p^*, T^*\right)$ and downstream $\left(p_e\right)$parameters and of the nozzle geometry (nozzle section with respect to the longitudinal coordinate, $A = A(x)$). This situation corresponds to curve 5 in Fig. 2; the pressure will drop in the first part of the nozzle after curve 4, the flow being supersonic up to the shock-wave. Through the normal shock-wave the pressure undergoes a jump, then following the 5-curve till the pressure p_e in the exit section.

3.2. Laval intake's starting. The Laval air intake with internal compression must realize the pressure variation after the same curve as shown in Fig. 2, but obviously in the opposite direction. In order to achieve a better correlation with the phenomena presented in the previous paragraph, but reversed as a direction of realization, it is assumed that, in the case of the studied convergent-divergent air intake, there is another Laval nozzle, which performs the supersonic velocity *V* and the air flow $\dot{m}_a$ necessary to operate the air intake at the nominal calculation mode. Therefore, one considers two succesive Laval nozzles (see Fig. 3), the first-one has constant geometry, while the second-one (which is the studied variable air intake) has variable geometry.

The critical section (the throat) of the first nozzle has the cross-section A_{cr1} determined by the condition that the nozzle must be able to drive the imposed air flow rate. The second air nozzle has variable throat cross-section A_{cr2} and will take up the air supplied by the first nozzle at the speed and at the flow rate imposed by this one.

Initially, it is considered that the air intake has the critical section "closed" (position 1), at its minimum value $\left(A_{cr2} < A_{cr1}\right)$, which is the value which corresponds to the critical flow regime in this section. The pressure distribution corresponds to the curve 1 in Fig. 3.

Further, the critical section of the variable nozzle is increased to a new position, denoted by *"cr"* when the equality $A_{cr2} = A_{cr1}$ is obtained. The airflow through the air intake has increased, compared to the previously described case; in addition, in both critical sections the sound speed is obtained.

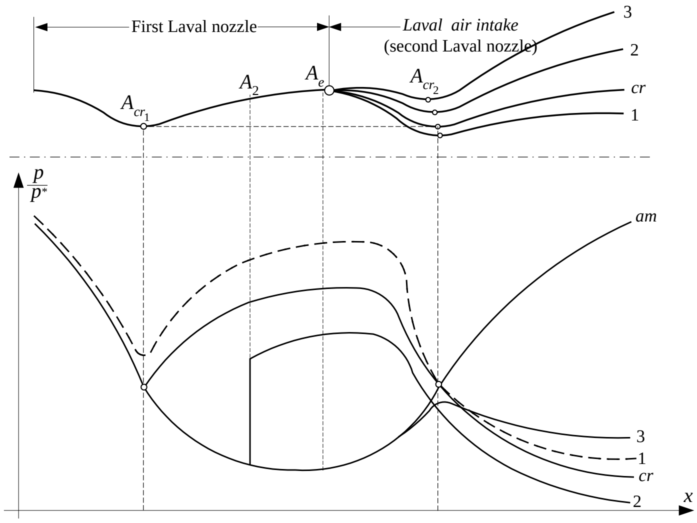

FIG. 3. Laval-type air intake starting process [8]

As in the first nozzle, in the divergent zone, the flow velocity is subsonic, in the second nozzle the air accelerates in its convergent zone (the curve denoted by *"cr"*).

If the critical area of the air intake opens even more, so that $A_{cr2} > A_{cr1}$, then a sudden depression wave occurs behind the first nozzle, which implies the occurrence of a normal shock-wave point in its divergent portion (in position A_2); behind the wave, the flow rebecomes subsonic and is compressed isentropically in the first nozzle's diffuser, then it accelerates to the sound speed in the throat (critical section) of the Laval intake, then accelerates further (curve 2 in Fig. 3).

From the written flow conservation equation for the two nozzles, it results:

$$\dot{m}_a = A_{cr1}\frac{p^*_{am}}{i^*_{am}} = A_{cr2}\frac{p^*_{av}}{i^*_{av}}, \tag{6}$$

and taking into account the fact that the total enthalpy does not change, it is obtained:

$$\frac{A_{cr2}}{A_{cr1}} = \frac{p^*_{am}}{p^*_{av}} = \frac{1}{\frac{p^*_{av}}{p^*_{am}}} = \frac{1}{\sigma^*_{us}}. \tag{7}$$

Therefore, since the shock-wave of the first nozzle diffuser moves outwardly, its greater the intensity and the total pressure loss coefficient σ^*_{us} decreases; consequently, the ratio $\frac{A_{cr2}}{A_{cr1}}$ increases, so the section A_{cr2} is growing. On the magnitude of the increasing opening of the variable section A_{cr2}, the shock-wave of the first nozzle diffuser is getting closer and closer to the exit from it, where the area of the section is A_{e1}; at a time, a small additional opening of A_{cr2}, the shock-wave is discharged from the first nozzle and "sent" to the terminal area of the second nozzle (the air intake) at the section A_{e2}, whose mode corresponds to curve 3 in Fig. 3. As a consequence, it can be stated that the critical area of the air intake varies between extreme values A_{cr1} and A_{e2}.

If a current section $A_x \left(A_x \in \left[A_{cr1}, A_{e2}\right]\right)$ is considered, from the equation of air's evolution, assumed to be isentropic, it is obtained

$$\frac{A_{cr1}}{A_x} = q(\lambda_x). \tag{8}$$

From the moment when the shock-wave was discharged from both nozzles, the reduction of the throat of the air intake would lead to the return of the shock-wave to the minimum section of the intake, in its divergent zone. When reating the value $A_{cr2} = A_{cr1}$, it is obtained the starting of the air intake (curve "am" in Fig. 3). Therefore, the starting of the air intake assumes a complex maneuver, initially complete opening (up to $A_{cr} = A_{1'}$), then closing, to the section A_{cr} that can support the air flow rate required for the engine. However, a small variation of the throat section or of the downstream pressure leads to the disengagement of the air intakes, which means the return on the *"cr"* curve, which produces an imbalance between the flow rate required by the engine and the flow provided by the air intake, sometimes resulting the engine unexpected shutting down.

4. INTAKE'S CONTROL LAW DESIGN

From the previously presented, it results that the starting of the Laval air inlet with internal compression is an extensive process, requiring a variation of its minimum section (throat) in both directions, initially increasing, then returning. In fact, the process resides in the repositioning, in the divergent zone of the air intake channel, of the normal shock wave, which initially was formed in front of the air intake.

4.1. Control law's limits establishing. For a certain but known flight regime, characterized by Mach flight number M_H (or velocity ratio λ_H), according to (8), it results

$$\frac{A_{cr}}{A_{1'}} = \frac{A_{cr}}{A_H} = q(\lambda_H), \tag{9}$$

where A_H is the area of the cross section of the current tube upstream of the intake, equal to $A_{1'}$ the area of the intake's input section. The size of this area is given by the required air flow rate, according to that flight regime.

To start the internal compression, in the first phase the shock wave must be "transferred" to the exit area of the divergent zone of the intake, so it is necessary to enlarge the critical section. This must be done in accordance with (8), to conserve the flow even behind the shock wave (already reached in the channel), where, according to Prandtl's law, the velocity coefficient is the inverse of the velocity coefficient before the shock wave

$$\frac{A_{cr}}{A_{1'}} = q\left(\frac{1}{\lambda_H}\right). \tag{9}$$

After the shock wave evacuation, the throat section must be reduced so that it reaches the initial value.

Taking into account the formulas (8) and (9), for each flight regime (for each M_H or λ_H), it is possible to identify the range of values for A_{cr} with respect to $A_{1'}$.

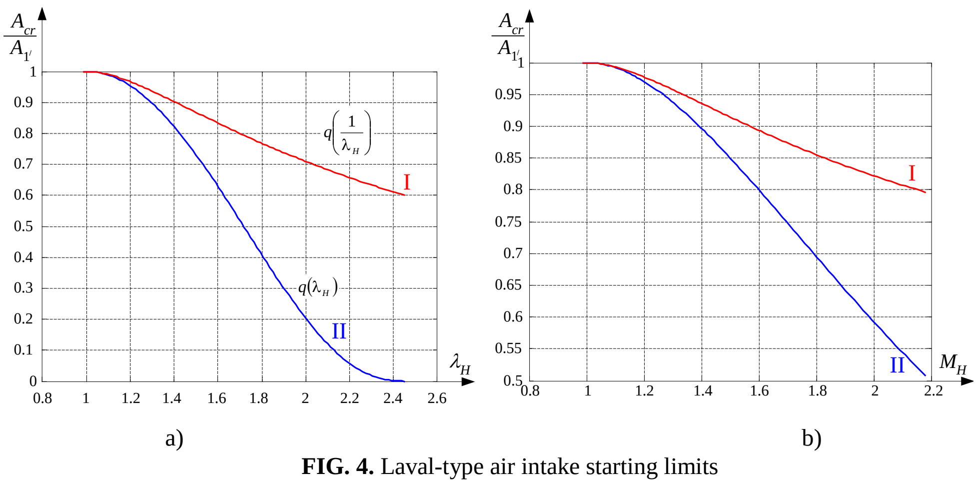

FIG. 4. Laval-type air intake starting limits

For a sequence of flight regimes, two curves (I and II in Fig. 4) are obtained, which determine the air intake with internal compression starting envelope. Inside this envelope the sarting is stable, varying only the intensity of the perrssure losses $\left(\sigma_{us}^{*}\right)$; the losses are even less as the operating mode of the intake approaches the curve I (where the losses are, under ideal conditions, null). Consequently, all adjustment and control laws must be within this envelope area. Curves in Fig. 4.a) are traced with respect to the velocity coefficient, while in Fig. 4.b) is the same envelope with respect to the Mach number, based on the connection between M_H and λ_H:

$$M_H = \sqrt{\frac{2\lambda_H^2}{\chi + 1 - (\chi - 1)\lambda_H^2}}\,. \tag{10}$$

It is precisely because once with the return to the I curve, when the isentropic compression is started, the air intake becomes very sensitive to the accidental variations of either the throat cross section, or the flight regime, losing its stabile operation; it is preferred to reduce the throat of the intake (to return to curve I) and to maintain a reserve with respect to the lower limit curve I $\left((A_{cr})_{real} > (A_{cr})_{nec}\right)$. In this way, the shock wave is fastened in the area of the throat, but in intake's divergent zone, with the consequence of the keeping the intake started, even under conditions of disturbance; it assures low total pressure losses, acceptable under conditions of stability to the action of the various disturbances.

4.2. Intake's work line. Based on the above considerations, it is possible to determine the air intake work line, to be drawn on the starting envelope; the complete work line is very complex, but some possible aspects of it are drawn on the starting envelope in Fig. 5.

The following important zones of the intake work line can be identified, depending on the flight speed (more precisely, depending on the Mach number):

a) starting the engine, corresponding to point A. Engine's start is facilitated by the presence of a significant dynamic compression component, if the aircraft whics uses tis device is already in flight. The intake must be fully open, so the critical area (the throat) is equal to the intake area;

b) acceleration to the sound speed, section A-B, when the air intake must hold the same aperture. At the end of accelerating, when the sound speed is reached, a normal shock wave occurs in front of the air intake;

c) acceleration in the supersonic mode, section B-C, until the shock wave is attached to the intake's lip. In this zone, the intake's throat must be gradually reduced (on curve I), following the increase of the speed.

To stabilize the shock-wave's position, once the Mach limit is reached, the throat section must close to point D, near the limit curve II. Point D is not on curve II, but there is a certain reserve, in order not to „destart" the intake;

d) the further acceleration on section D-E is done with the same throat cross-section value, on a horizontal line in the diagram in Fig. 5, to the restraint in the proximity of the curve I, with the evacuation of the shock-wave from the intake;

e) accelerating on the EF line, graduated with the throat's section drop, on a parallel curve to curve I and very close to it. When reaching the maximum speed (maximum Mach number), the throat section can be reduced to curve II (vertical FG) to start the isentropic flow in the intake. However, the G point is not on the curve II, in order to keep a reserve and avoid disruption in the event of disturbances occurance. One may affirm that the G point represents the starting regime of the isentropic flow through the Laval air intake.

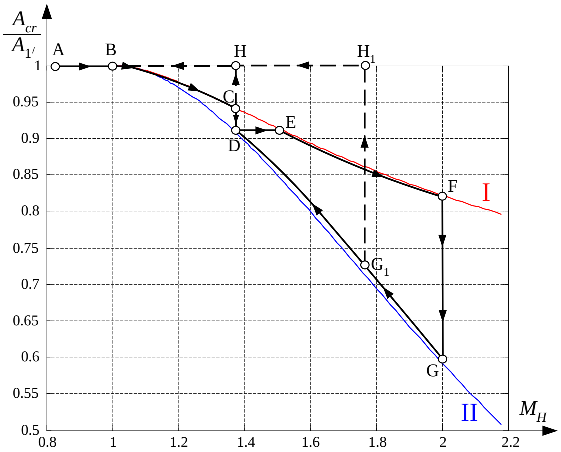

FIG. 5 Laval-type air intake work lines used as control law(s)

In the situation where the deceleration of the airplane is desired, then the operating point of the Laval Intake must be maintained within the starting envelope, as far as possible on the curve II. For the same reasons as mentioned above, a reserve is kept against the curve II towards the inside of the envelope, therefore any deceleration operation, which can not be safely performed on the curve II, must be made on a close curve, respectively, on the GD path, the current point G_1 being displaceable between the two limits. Further, if the subsonic regime is to be regained, then the reverse path might be followed, such as the curve D-C-B-A, or the point A might be moved to the left; in fact, in transonic or subsonic mode, the air inlet is completely open. If the deceleration occurs suddenly, commanded or accidentally, then the air intake must be open to restore the starting on one of the routes in Fig. 5 (either on the G_1-H_1-H-B route, where G_1 can have any position between G and D or on the alternative route D-C-H-B, if the deceleration is made from low supersonic regime).

CONCLUSIONS

It can be argued that a Laval-type air intake with fixed geometry can only provide a single flight regime and operating mode of the engine, so it is imperative to use variable-geometry air intakes, with their minimum section (throat) of variable dimensions. Two possible forms of the intake are: axisymmetric, or plane-parallel.

However, if a throat adjustment method is possible, the Laval-type inlet control becomes possible; the work-line(s) for such an intake was (were) determined, correlated to the flight regime, which made possible a control law issuing, as well as an appropriate control architecture design; anyway, the starting problem must always be overcome and the control laws must follow the work lines inside the starting (operational) envelope, in order to keep always correlated the engine's air needs and the intake's air offer with an appropriate structure.

It is very difficult (virtually impossible) to construct an axisymmetric air inlet whose throat can be adjusted to be able to adapt to various flight regimes. The planar parallel intakes can be manufactured with much simpler geometry, since they have the frontal section of a rectangular shape of constant depth, and the scaling of their throat requires only the scaling of the other rectangle dimension (the height). However, when the internal compression is combined with the external compression (in the mixed compression inlets), one can imagine a special form of its centerbody, which, together with the shape of the air intake and the channel, generates a Laval-type nozzle, with variable minimum section (both in size and axial position) by the favorable repositioning of the central body [13, 14, 16]. Starting problems are also issuing both for internal and mixed compression inlets.

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