AUTOMATIC CONTROL SYSTEM FOR SUPERSONIC INLET'S CENTERBODY'S POSITIONING

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DOI: 10.19062/2247-3173.2018.20.34

Abstract: *The paper deals with an automatic system meant to control an air inlet designed for a supersonic aircraft. Starting from the system composition and its constructive scheme, the mathematical model was built up and the transfer function was also determined. Mathematical model's coefficients were calculated or estimated based on inlet's control law and on other similar systems coefficients calculation. Some simulation were performed and the stability and the quality of the control system were evaluated, for different flight regimes. The study is useful for similar inlet's control architecture possibilities evaluation.*

Keywords: *supersonic, inlet, centerbody, control, Mach number, actuator, feedback, step response.*

1. INTRODUCTION

Inlet control systems are built up in a wide range of architectures and operational principles, depending on the type of the aircraft which uses it, on the type of the assisted aircraft engine, on the specific inlet architecture, as well as on their specific positioning on the airframe. Such systems, that assist various supersonic inlets, are presented and studied in [1, 11-16]. The possibilities of control for an aircraft supersonic inlet, in order to assure the suitable balance of the engine's necessary air flow rate and, respectively, the inlet's delivered air flow rate, are various, such as: the flow cross-section area's control by the spike or the centerbody positioning [1, 14, 15], respectively by the intake's cowl positioning [14], as well as the inner minimum cross-section area control by the inner diaphragm's positioning [11, 12].

Most of these control systems are based on hydraulic actuators; however, electric actuators are also a reliable alternative, depending on the necessary power for the mobile parts displacement. The above-mentioned control systems are hydromechanical-type, but their transducers and command elements may be hydraulic, pneumatic or even electric.

The inlet control system studied in this paper is a mixed-one, having a hydro-mechanical actuator, pneumatic pressure sensors, as well as electrical programming and command block and feedback converter. These elements are individually or combined studied in [1, 5, 11, 13], for different applications, such as follower systems, feed-back or/and feed-before control systems.

2. INLET CONTROL LAW

The control law for the studied inlet was determined in [15] with respect to aircraft flight regime, consisting of inlet's centerbody's positioning with respect to the freestream in front of the inlet Mach number (which is the same with the flight Mach number for a frontal inlet, mounted in the front of aircraft's fuselage).

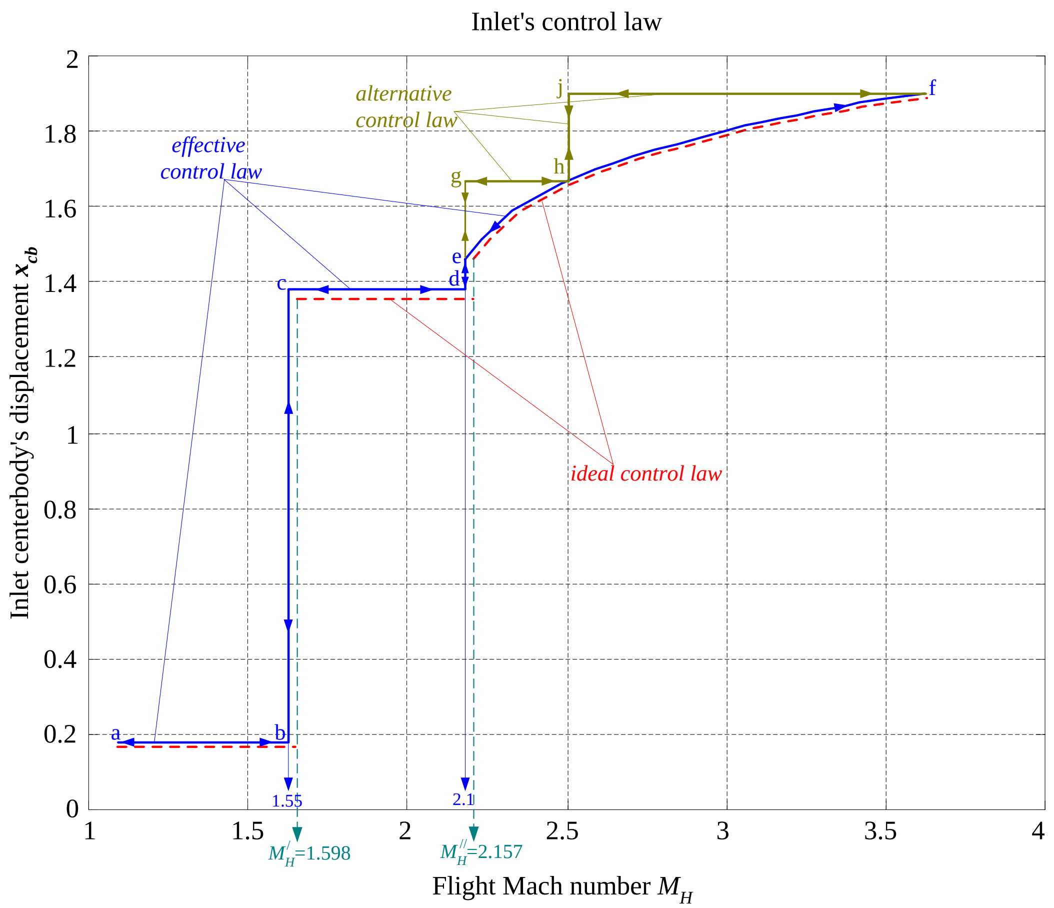


FIG. 1. Inlet's control law possibilities

The theoretical control law, as determined in [15], is graphically depicted in Fig. 1 with red dashed line; it is noteworthy that the law is a discontinuous-one, having two flat zones and and a non-linear zone.

The effective (real) control law, used for the inlet's control (inlet's adapting at various flight regimes), is a little different than the theoretical-one, because of various flight conditions changing and because of a lot of aerodynamic and engine operation constraints. Thus, the effective control law should have a different graphical shape, as depicted in Fig. 1 with continuous blue line (a-b-c-d-e-f).

The effective control law should follow the ideal law, but some differences are to be highlited. Firstly, the flat zones a-b and c-d, as well as the non-linear zone e-f, are developed at higher levels, which means that the centerbody has small extra-displacements, for safety operation. Secondly, in order to avoid the accidentally penetration of the external shock-waves into the air inlet, the "jumps" b-c and d-e must be realized earlier than at the critical Mach numbers $M_H^{/}$ and $M_H^{//}$; in fact, the new jump Mach number values are $M_H^{/}=1.55$ instead 1.598, respectively $M_H^{//}=2.1$ instead of 2.157.

The non-linear zone e-f of the ideal control law may be mathematically described (as presented in [15]) by the formula:

$$x_{cb}(M_H)=0.0816\times M_H^4-0.797\times M_H^3+2.5847\times M_H^2-2.617\times M_H+1.307\,, \tag{1}$$

while the effective law must be translated at bigger values, so the term 1.307 in Eq. 1 becomes 1.315. However, it is difficult to realize this zone with accuracy, so an alternative control law may be issued, as presented in Fig. 1 with continuous green line.

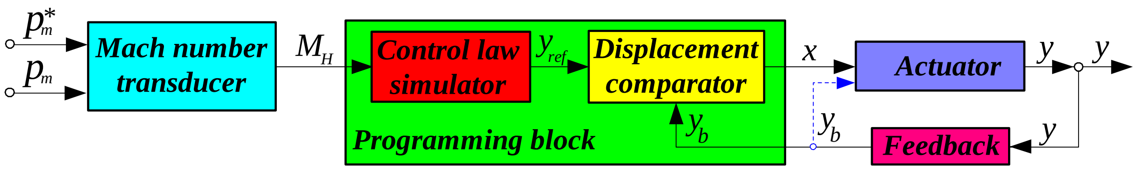


FIG. 2. Inlet's control system operational block diagram

This alternative law must "cover" the non-linear zone, approximating it by two flat zones (g-h and j-f) and an additional "jump" h-j at $M_H^{///} = 2.5$.

3. AUTOMATIC SYSTEM PRESENTATION

Automatic control system operational diagram is depicted in Fig. 2. As presented, the control system consists of: a) the Mach number transducer; b) the programming block ; c) the hydraulic actuator (with or without inner feedback); d) centerbody's position feedback. One has used as input/output signals the formal-ones (such as the Mach number or displacements), while many of the operational blocks are converting these various signals into electric-ones.

The Mach number transducer converts the pressure signals (total pressure p_m^* and static pressure p_m, obtained by Pitot-tube intake) into an electrical signal U_M proportional to the flight Mach number in front of the inlet M_H. Such a transducer, or similar ones, are described and studied in [5, 9, 13]; most of them are included in a much complex aerodynamic system for flight altitude, flight speed (or flight Mach number) and attack angles measuring, which obtains pressure information from an embedded aerodynamic probes network.

This electrical signal becomes the input of the programming block. This block consists of a control law simulator and a comparing block. The control law simulator should give the necessary centerbody displacement y_r, determined with respect to the measured flight Mach number M_H; in fact, the control law simulator use the electrical signal U_M for another electrical signal issuing, the U_{yr} – voltage, which is proportional to the necessary centerbody's displacement y_r. This signal is the input of the displacement comparator, where it is compared to another electrical signal U_y, which is the signal proportional to the realized centerbody's displacement y, converted by the feedback block into an electrical voltage; the result of the comparison $U_{yr} - U_y$ is amplified and then converted by the displacement comparator through a logometric system into a mechanical signal, the displacement x.

This x – displacement becomes the input of the actuator's distributor (slide valve); the actuator needs a high power to displace the centerbody, so it was chosen as hydraulic-type, being supplied by aircraft hydraulic system, or it could have its own pump. The actuator's distributor is a mechanical-one and its displacement x, given by the comparator, is proportional to the centerbody's displacement error. The actuator may have an inner feedback (as presented and studied in [13], highlighted in Fig. 2 by dashed line), or it may have not, the centerbody's position feedback being used only by the comparing block.

4. SYSTEM'S MATHEMATICAL MODEL

A simplified mathematical model of the centerbody's position control system may be obtained if one uses the already determined models for each one of system's parts.

4.1. Mach number transducer's model. The transducer has the main role to determine the value of the flight Mach number, based on aerodynamic information (total and static air-pressure) and to convert it into a voltage signal. Its mathematical model is determined in [5] and has the form

$$\overline{M}_H(\mathrm{s}) = \frac{k_{pt}}{\tau_{MH}\mathrm{s}+1}\overline{p}_m^*(\mathrm{s}) - k_p\overline{p}_m(\mathrm{s}), \tag{2}$$

$$\overline{U}_M(\mathrm{s}) = k_{UM}\overline{M}_H(\mathrm{s}), \tag{3}$$

where k_{pt}, k_p, k_{UM} are gains, τ_{MH} – transducer's time constant with respect to the total pressure, $\overline{M}_H$ – Mach number's dimensionless parameter, $\overline{p}_m, \overline{p}_m^*$ – pressures' dimensionless parameters, $\overline{U}_M$ – transducer's output voltage dimensionless parameter. As presented, the transducer has an aerodynamic block and a converter.

4.2. Programming block model. The programming block consists of two important parts: the control law simulator, which gives the imposed centerbody's displacement with respect to the Mach number, respectively the displacement comparator, which compares the imposed centerbody's displacement to the effective centerbody's displacement and gives the input signal for the actuator's slide-valve.

The control law simulator is, in fact, a block (computer) which calculates the centerbody's displacement with respect to the flight Mach number M_H (using the polynomial (1) and/or the graphics in Fig.1) and supplies the comparator with the U_{yr} – reference voltage, which is proportional to the reference centerbody's displacement y_r (the term x_{cb} in Fig. 1 or in Eq. (1)):

$$\overline{U}_{yr}(\mathrm{s}) = k_{Myr}\overline{U}_M(\mathrm{s}), \tag{4}$$

where $\overline{U}_{yr}$ is the reference dimensionless voltage and k_{Myr} – the gain calculated from the control law, which may be determined as the derivative of the polynomial function which describes the control law.

The displacement comparator block is, in fact, a logometric comparison system, comparing the displacement signal voltage U_y to the reference signal voltage U_{yr}. The algebraic sum $U_{yr} - U_y$ may be positive, negative or zero. The zero sum corresponds to the steady state regime, when the flight Mach number is constant and the centerbody position must be kept the same. For other $U_{yr} - U_y$ values the actuator should become operational and move the centerbody into the suitable direction and with the correct distance.

Displacement comparator's model is a linear-one and may be described as

$$\overline{x}(\mathrm{s}) = k_{Ux}\left[\overline{U}_{yr}(\mathrm{s}) - \overline{U}_y(\mathrm{s})\right], \tag{5}$$

where k_{Ux} is comparator's gain and it is necessary for the signal amplifying, in order to assure enough power and stroke for the distributor's slide-valve.

4.3. Actuator's model. For the hydraulic actuator, without (Eq. (6)) or with rigid feedback (Eq. (6$^{/}$)), one has determined the model in [13] as follows:

$$k_x\overline{x}(\mathrm{s}) = (\tau_{Ap}\mathrm{s} + \rho_a)\overline{y}(\mathrm{s}), \text{ or} \tag{6}$$

$$k_x \bar{x}(s) - \bar{z}(s) = (\tau_{Ap} s + \rho_a)\bar{y}(s), \qquad (6')$$

where τ_{Ap} is the hydraulic actuator's time constant, ρ_a – actuator's stability constant, $\bar{y}$ – actuator's rod displacement dimensionless parameter, k_x – actuator' slide-valve's gain, $\bar{z}$ – actuator's rigid feedback dimensionless parameter (if the feedback exists).

4.4. Feedback equations. Actuator's rod displacement y must be measured and used as feedback for the programming block. It is very difficult to perform a mechanical measurement, so the feedback uses an electric potentiometer (as described and studied in [5]) which transforms the mechanical signal of the displacement into an electric voltage signal U_y; usually, for small y – displacements, the used potentiometer is a linear-one, but if the displacements have significant values, the used potentiometers may be non-linear (logarithmic), the feedback becomes also non-linear and the programming block's control law simulator must be modified.

$$\bar{U}_y(s) = k_{yU} \bar{y}(s), \qquad (7)$$

where k_{yU} is the potentiometer's gain.

Actuator's feedback is a mechanical-one, being realized by a rocking lever (as presented in [1, 13,14]) and its equation is

$$\bar{z}(s) = k_{\rho l} \bar{y}(s), \qquad (8)$$

where $k_{\rho l}$ – actuator's rigid feedback gain.

4.5. System's transfer function. Using the above-presented mathematical model's equations, one has built up the block diagram with transfer function, as depicted in Fig. 3.

Based on the above-presented equations, one has determined a simplified form of the mathematical model, which excludes the aerodynamic transducer, considering only the converter, the programming block and the actuator, as follows:

$$\bar{y}(s) = \frac{1}{\tau_a' s + \rho_a'} \bar{M}_H(s), \qquad (9)$$

System's transfer function $H_M(s)$, with respect to the freestream Mach number (flight Mach number), for an actuator without inner feedback (AWFB), becomes:

$$H_M(s) = \frac{1}{\tau_a' s + \rho_a'}, \qquad (10)$$

where τ_a' – time constant, ρ_a' – stability constant, their expressions being, as follows:

$$\tau_a' = \frac{\tau_{Ap}}{k_x k_{Ux} k_{Myr} k_{UM}}, \qquad (11)$$

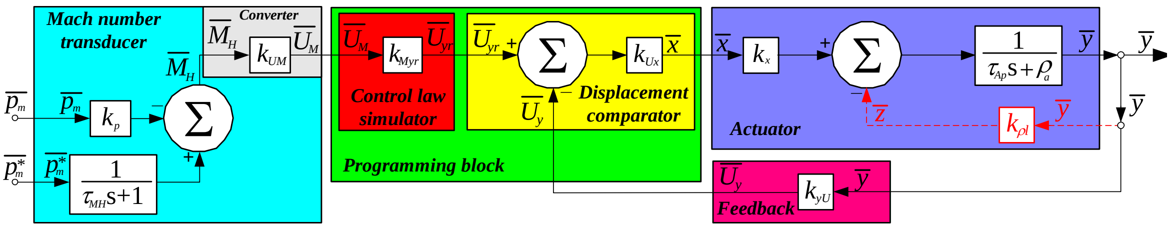


FIG. 3. Inlet's control system block diagram with transfer functions

$$\rho_a^{/}=\frac{\rho_a+k_x k_{Ux} k_{yU}}{k_x k_{Ux} k_{Myr} k_{UM}}. \tag{12}$$

If the actuator has a mechanical inner feedback (AFB, as presented in Fig. 3, red dashed line inside the *Actuator*-block), the transfer function has the same form as in Eq. (10), its time constant has the same expression as in Eq. (11), but the stability constant becomes

$$\rho_a^{//}=\frac{\rho_a+k_{\rho l}+k_x k_{Ux} k_{yU}}{k_x k_{Ux} k_{Myr} k_{UM}}=\rho_a^{/}+\frac{k_{\rho l}}{k_x k_{Ux} k_{Myr} k_{UM}}, \tag{13}$$

which means that the presence of the feedback increases the stability constant value.

5. ABOUT SYSTEM'S STABILITY AND QUALITY

System's transfer function with respect to the flight Mach number is a first order one; its stability is fulfilled if the coefficients $\tau_a^{/}$ and $\rho_a^{/}$ (respectively $\rho_a^{//}$) have the same sign. As far as $\tau_a^{/}$ is a time constant, which is always positive and the quantities involved in $\rho_a^{/}$ and/or $\rho_a^{//}$ expressions are always positive, one may conclude that the system is a stable-one, its stability being asymptotic-type.

System's quality (system's time behavior) shall be estimated using the unitary step input (Heaviside step function as input for the system), which means a hypothetical sudden modifying of the flight Mach number. System's output was considered the actuator's rod displacement dimensionless parameter, which is the same parameter as the inlet's centerbody's positioning. Such a simulation was performed, for both of actuator's options (with or without rigid feedback), for multiple flight situations; one has considered the most important flight regimes: the nominal-one (when $M_H=3.3$), the intermediate regime ($M_H^{///}=2.5$), the medium supersonic regime ($M_H^{//}=2.1$) and the low supersonic regime ($M_H^{/}=1.55$), that means the nominal regime and the centerbody's repositioning regimes.

System's coefficients were calculated using the control law in Fig. 1 or were estimated using some other studies [1, 11, 12, 14]. Simulation results are presented in Fig. 4.a)…d), corresponding to the above-mentioned flight regimes.

For the most frequently used flight regime (see Fig. 4.a), no matter the actuator architecture, the system stabilizes with static error (4.8% for AFB, 6.3% for AWFB), the values of the settling times being nearly the same, around 3.0 seconds.

For an intermediate supersonic flight regime, the asymptotic aperiodic stabilization maintains; both static errors are growing (7.3% for AFB, 9.8% for AWFB), while the settling time has a small increasing (around 3.3 seconds).

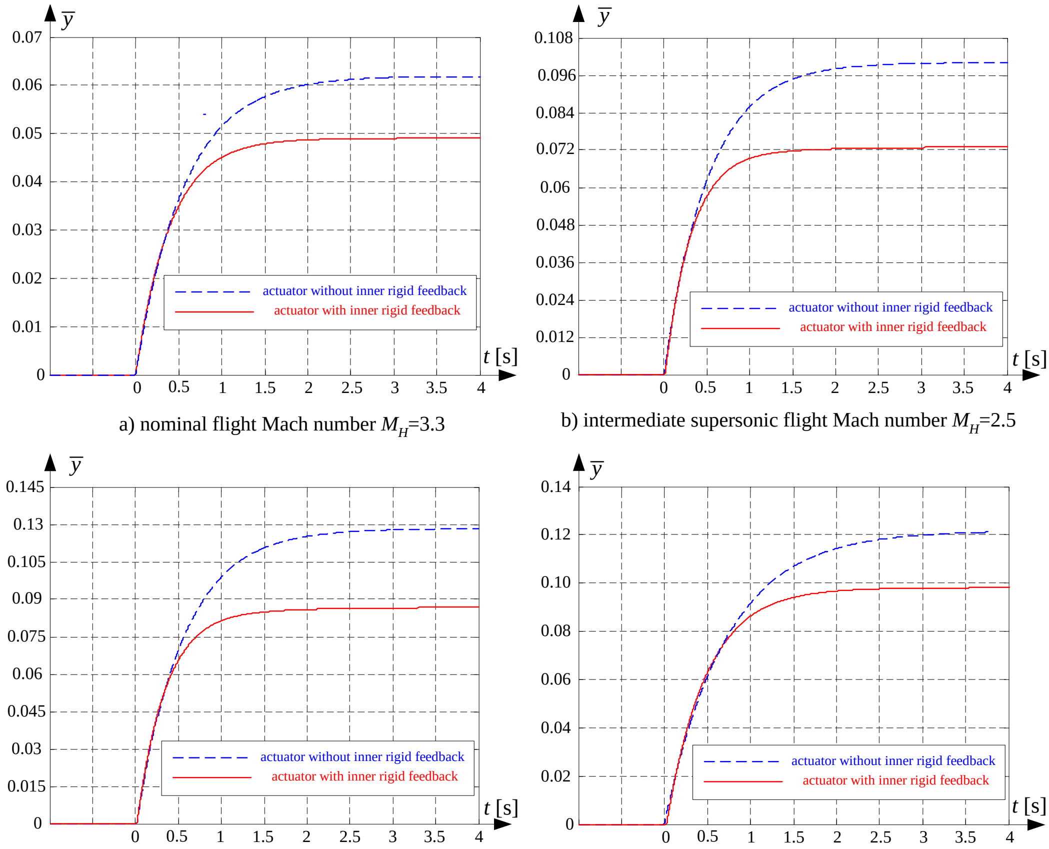
If the flight regime becomes less intense ($M_H^{//}=2.1$), the trends are maintaining, so the static errors become 8.8% for AFB and 12.8% for AWFB, while settling time values become 3.3 seconds for AFB, respectively 3.5 seconds for AWFB.

When the aircraft flies at low supersonic regime ($M_H^{/}=1.55$), control system has the same behavior, but bigger static errors (9.8% for AFB, 12.2% for AWFB), while the settling times are the biggest (3.6 seconds for AFB, respectively 3.8 seconds for AWFB).

CONCLUSIONS

One of nowadays most important issues of the high speed flights is how to obtain the necessary thrust, which needs special thermo-hydro-dynamic conditions.

These conditions concern the maintenance of pressure and air density inside the engine, no matter the flight regime, condition very difficult to be accomplished as long as the flight regime parameters vary in a wide range of values. The necessary air mass flow rate for the engine of an aircraft is ensured by engine's inlet; if supersonic, its architecture and operation mode are all the more important. In fact, the inlet is the connector between engine air necessities and the available air mass flow rate and acts like an interface.



a) nominal flight Mach number M_H=3.3

b) intermediate supersonic flight Mach number M_H=2.5

c) medium supersonic flight Mach number M_H=2.1

d) low supersonic flight Mach number M_H=1.55

FIG. 4. Control system's step response for different flight regimes

Control law, consisting of inlet's spike positioning with respect to the flight regime, is not a continuous curve (as Fig. 1 shows); it has two or three discontinuity points, which corresponds to the critical regimes (when the conical shock-waves are to be detached) and two flat zones, as well as a non-linear zone.

For all flight regimes the control system is an asymptotic stable-one, presenting an aperiodic behavior, because of its first order transfer function.

The system is a static-one, its static errors having acceptable values (from 4.8% to 12.8%), the smaller values being obtained when an actuator with inner feedback is used; system's settling time has also acceptable values, around 3.0 s for high flight speeds and around 3.8 s for low flight speeds, which proves that the system has a better behavior at high flight speeds. From the stability and quality points of view, the chosen control system has obtained acceptable performances (static errors and settling time values) in the entire flight regimes range.

A similar study may be performed if one considers both the aerodynamic transducer and the electric converter as Mach number estimators; consequently, the system will have two inputs (the static and the total pressure parameters), two transfer functions and both of these transfer functions will have a second order characteristic polynomial, in which case the stability and quality studies become more complicated.

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