Fuel Injection Controller with Barometric and Air Flow Rate Correctors

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Abstract: This paper presents two methods of an engine controller operating correction, using two equipments based on air pressure measurement. One has studied a fuel flow rate controller based on the differential pressure control meant to assist a turbo-jet engine, which has two correctors: a barometric-one, in order to correct the controller flight regime behavior and a pressure ratio-one, in order to correlate the fuel flow rate and the compressor air flow rate. The correctors’ equation were determined and, based on it, the new form of the mathematical model and the new form of the block diagram with transfer functions. Some studies, concerning the system’s quality were realized – system’s step response for flight regime and/or throttle’s position step input; the performed simulations revealed system’s improvements. The studied correctors could be incorporated into other similar jet engines’ control systems.

Key-Words: jet engine, control, fuel, airflow rate, pressure ratio, actuator, corrector, speed, flight regime.

1. Introduction
Fuel injection controllers for aircraft engines are meant to assist the engine operating during a large range of rotation speeds and flight regimes (flight altitudes and flight speeds). Most of them are controlling the engine speed using as main parameter the injected fuel flow rate, through direct or indirect methods. Their correct operating depends on their interaction with the engine (the controlled object) and with the fuel pump, all together representing the control system.

So, the fuel pumps are integrated in the jet engine’s control system, the fuel pump being turned round by the engine’s shaft (obviously, through a gear box); consequently, the pump rotation speed is proportional (sometimes equal) to the engine’s speed \( n \), which is the engine’s most frequently controlled parameter. The engine’s speed controller must command the other fuel pump control parameter (the plate angle or the discharge orifice width).

2. Problem formulation
For most of the nowadays operating controllers, designed and studied for modern jet engines, the behavior is satisfying, because the controlled systems become stable and their main output parameters have a non-periodic (or asymptotic) stability. However, some observations regarding their behavior with respect to the (aircraft and engine) flight regime ([6], [8], [10]) lead to the conclusion that the more intense is the flight regime, the higher are the controllers’ static errors, which finally asks a new intervention (usually from the human operator, the pilot) in order to re-establish the desired output parameters levels. The simplest solution for this issue is the flight regime correction, which means the integration in the control system of new equipment, which should adjust the control law. These equipments are known as barometric (baro-altimetric or barostatic) correctors.

In the mean time, some unstable engines or some unstable fuel pump-engine connections, even assisted by fuel controllers, could have, as controlled system, periodic behavior, that means that their output main parameters’ step responses presents some oscillations, as fig. 1 shows. The immediate consequence could be that the engine, even correctly operating, could reach much earlier its lifetime ending, because of the supplementary induced mechanical fatigue efforts, combined with the thermal pulsatory efforts due to the engine combustor temperature periodic behavior.

As fig. 1 shows, the engine speed \( n \) and the combustor temperature \( T_3 \) (see fig. 1.b), as well as the fuel differential pressure \( p_d \) and the pump’s discharge slide-valve displacement \( y \) (see fig. 1.a) have periodic step responses and significant
overrides (which means a few short time periods of overspeed and overheat for each engine full acceleration time).

The above described situation could be the consequence of a miscorrelation between the fuel flow rate (given by the system controller-pump) and the air flow rate (supplied by the engine’s compressor), so the appropriate corrector should limit the fuel flow injection with respect to the air flow supplying.

The system depicted in fig. 2 has as main control equipment a fuel injection controller (based on the differential pressure control) and it is completed by two correction equipment (correctors), one for the flight regime and the other for the fuel-air correlation. System’s new model and quality will be studied in the next sections.

**Control system’s main parts**

I-differential pressure transducer; II-actuator; III-actuator’s feedback; IV-fuel injector; V-fuel pump; VI-fuel tank; VII-flight regime corrector; VIII-air flow rate corrector.

1-lever (throttle bounded); 2-cam; 3-spring; 4, 13-flap with hemispherical lid; 5,6-drossels; 7-elastic membranes; 8-intermembrane rod; 9-actuator’s piston; 10-calibrated orifice; 11-profiled rod (needle); 12-springs; 14-drossel; 15-injector final orifice; 16-injector’s drossel; 17-fuel pump’s exhaust pipe; 18-injector’s discharge pipe; 19-low pressure fuel pipes (controller’s discharge pipes); 20-transducer’s pressure chambers; 21-open capsule; 22-aneroid capsule; 23-common rod; 24-elastic protection bags; 25-pressure ratio transducer’s rod; 26-transducer’s spring; 27-transducer’s elastic membrane; 28,29-drossels
3. System’s mathematical model

Basic system (controller without correctors+fuel pump+injectors) non-dimensional linearized mathematical model consists of

\[ \bar{u} = k_{u0} \bar{\theta}, \]  
\[ \bar{p}_i = k_{dp} \bar{p}_p - k_{d\bar{u}} \bar{p}_i, \]  
\[ \bar{c}_x = k_{cx} \bar{p}_u - k_{d\bar{u}} \bar{c}_x, \]  
\[ (\tau_s + 1)\bar{p}_R = k_{1p} \bar{p}_p - k_{1x} - k_{1y} (\tau_s + 1)\bar{y}, \]  
\[ (\tau_p + 1)\bar{p}_p = k_{2p} \bar{p}_p + k_{2R} \bar{p}_R + k_{2Q} \bar{Q}_p, \]  
\[ (T^2 s^2 + 2\omega_0 T_s + 1)\bar{y} = k_{3y} \bar{p}_R - k_{3p} \bar{p}_p, \]  
\[ \bar{Q}_p = k_{p0} \bar{p}_i, \]  
\[ (\tau_s + 1)\bar{p}_R = k_{3p} \bar{p}_p - k_{3x} \bar{y}. \] 

The above used annotations are

\[ k_{u0} = k_{\theta0} \frac{u_0}{\bar{u}_0}, \quad k_{sd} = \frac{S_{n0} P_{i0} d_0}{k_{r1} A_0 X_0}, \quad k_u = \frac{u_0}{\bar{u}_0}, \quad k_{dp} = \frac{p_{i0}}{p_{d0}}, \]  
\[ k_{dir} = \frac{P_{i0}}{p_{d0}}, \quad \tau_R = \frac{\beta V}{k_{RP} + k_{xR} + k_{2R}}, \quad \tau_p = \frac{\beta V}{k_{RP} + k_{pT}}, \]  
\[ k_{1p} = \frac{k_{RP} \bar{p}_p}{(k_{RP} + k_{xR} + k_{2R}) \bar{p}_R}, \quad k_{1y} = \frac{S_{d1} \bar{y}}{k_{2y} \bar{y}}, \]  
\[ k_{1x} = \frac{k_{xR} \bar{x}_0}{k_{RP} + k_{xR} + k_{2R}} \bar{p}_R, \quad k_{2p} = \frac{k_{pT} \bar{p}_0}{k_{RP} + k_{pT}} \bar{p}_R, \]  
\[ k_{2R} = \frac{k_{RP} \bar{p}_R}{(k_{RP} + k_{pT}) \bar{p}_p}, \quad k_{2Q} = \frac{k_{pT} \bar{Q}_0}{(k_{RP} + k_{pT}) \bar{p}_p}, \]  
\[ T_y = \sqrt{m}, \quad 2\omega_0 T_s \bar{y} = \frac{\bar{c}}{k_{1y} + k_{2y}}, \quad k_{1y} = \frac{S_{d1} \bar{y}}{k_{2y} \bar{y}}, \]  
\[ k_{3y} = \frac{k_{y0} \bar{y}}{k_{pT} + k_{xR} + k_{Q0}} \bar{p}_0, \quad k_{3p} = \frac{n_0 (\bar{c} \bar{Q}_p)}{k_{pT} + k_{xR} + k_{Q0} \bar{p}_0}, \]  
\[ k_{3y} = \frac{k_{y0} \bar{y}}{k_{pT} + k_{xR} + k_{Q0}} \bar{p}_0, \quad k_{3p} = \frac{n_0 (\bar{c} \bar{Q}_p)}{k_{pT} + k_{xR} + k_{Q0} \bar{p}_0}. \] 

As fig. 2 shows, the correctors have the active parts bounded to the 13-lever (hemispherical lid’s support of the nozzle-flap actuator’s distributor). So, the 13-lever’s positioning equation should be modified, according to the new pressure and forces distribution.

**Case a) controller with barometric corrector**

The barometric corrector consists of an aneroid (constant pressure) capsule and an open capsule (supplied by a \( p_1^* \) - total pressure intake), bounded by a common rod, connected to the 13-lever.

The total pressure \( p_i^* \) (air’s total pressure after the inlet, in the front of the engine’s compressor) is an appropriate flight regime estimator, having as definition formula

\[ p_i^* = p_H \Pi (M_H) \sigma_c^*, \] 

where \( p_H \) is the air static pressure of the flight altitude \( H \), \( \sigma_c^* \) – inlet’s inner total pressure lose coefficient (assumed as constant), \( M_H \) – air’s Mach number in the front of the inlet, \( k \) – air’s adiabatic exponent and

\[ \Pi (M_H) = \left( 1 + \frac{k - 1}{2} M_H^2 \right)^{\frac{k}{k - 1}}. \]

The new equation of the 13-lever becomes

\[ S_R p_R - S_p p_p = m \frac{d^2 y}{dt^2} + \frac{2}{\bar{c}} \frac{dy}{dt} + (k_{1y} + k_{2y}) y - S_H (p_i^* - p_a) \frac{l_2}{l_1}, \]

where \( p_a \) is the aneroid capsule’s pressure and, after the linearization and the Laplace transformer applying, its new non-dimensional form becomes

\[ T^2 s^2 + 2\omega_0 T_s + 1 \bar{y} = k_{3y} \bar{p}_R - k_{3p} \bar{p}_p - k_{3H} \bar{p}_i, \]

and will replace the (6)-equation, where

\[ k_{3H} = \frac{S_H P_{i0}^* l_2}{(k_{1y} + k_{2y} \bar{y}) \bar{y} l_2}. \]

**Case b) controller with air flow rate corrector**

The air flow rate corrector consists of a pressure ratio transducer, which compares the realized pressure ratio value for a current speed engine to the preset value. The air flow rate \( Q_a \) is proportional to the total pressure difference \( p_2^* - p_1^* \), as well as to the engine’s compressor pressure ratio \( \sigma_c^* = \frac{p_2^*}{p_1^*} \).

According to the compressor’s universal characteristics ([4],[8]), for a steady state engine regime, the air flow rate depends on the pressure ratio and on the engine’s speed \( Q_a = Q_a (\sigma_c^*, n) \). The air flow rate must be correlated to the fuel flow rate \( Q_f \), in order to keep the optimum ratio of these values. When the
correlation is not realized, for example when the fuel flow rate grows faster/slower than the necessary air flow rate during a dynamic regime (e.g. engine acceleration/deceleration), the corrector should modify the growing speed of the fuel flow rate, in order to re-correlate it with the realized air flow rate growing speed. Modern engines’ compressors have significant values of the pressure ratio ([4],[8],[10]), from 10 to 30, so the pressure difference \( p_2^* - p_1^* \) could damage, even destroy, the transducer’s elastic membrane and get it out of order. Thus, instead of \( p_2^* \)-pressure, an intermediate pressure \( p_f^* \), from an intermediate compressor stage “f”, could be used, the intermediate pressure ratio \( \pi_f^* = \frac{p_f^*}{p_1^*} \) being proportional to \( \pi_c^* \).

The intermediate stage is chosen in order to obtain a convenient value of \( p_f^* \), around \( 4 \times p_1^* \). Both values of \( p_f^* \) and \( p_2^* \) are depending on compressor’s speed (the same as the engine speed \( n \)), as the compressor’s characteristic shows; consequently, the air flow rate depends on the above mentioned pressure (or on the above defined \( \pi_c^* \) or \( \pi_f^* \)). The transducer’s command chamber has two drossels, which are chosen in order to obtain critical flow through them, so the corrected pressure \( p_c^* \) is proportional to the input pressure:

\[
p_c^* = \frac{S_{28}}{S_{29}} p_f^*,
\]

where \( S_{28}, S_{29} \) are 28 and 29-drossels’ section values. Consequently, the transducer operates like a \( \pi_c^* \) based corrector, co-relating the fuel flow rate (necessary flow rate) and the air flow rate (delivered flow rate). So, the corrector’s equations are ([10]):

\[
p_c^* = p_z^*(n) \quad \text{or} \quad p_f^* = p_f^*(n), \tag{18}
\]

which becomes, after transformations,

\[
\pi_f^* = k_{fn} \pi_c^*, \tag{18'}
\]

\[
x_f = k_x \pi_f^* = k_gf \left( \frac{p_f^*}{p_1^*} - \frac{1}{k_{1f}} \right),
\]

where \( k_{fn} = \frac{c_0 p_{f1}}{\theta \partial p_f^*/\partial n} \). The new form of (6)-equation becomes

\[
S_R p_R - S_p p_p = m_s \left( \frac{d^2 y}{dt^2} + \xi \frac{dy}{dt} + (k_{1f} + k_{r2}) \right) - S_{mp} \left( p_c^* - p_1^* \right) \frac{l_6}{l_2},
\]

where \( S_{mp} \) is the transducer’s membrane surface area. After linearization and Laplace transformer applying, its new non-dimensional form becomes

\[
\left( T^2 s^2 + 2 \alpha_0 T s + 1 \right) \bar{y} = k_{1f} \bar{P}_R - k_{yp} \bar{P}_p - \left( k_{g} \bar{P}_f - k_{1f} \bar{P}_1 \right),
\]

where

\[
k_g = \frac{S_{mp} P_{f10} k_{sf} l_6}{(k_{1f} + k_{r2}) y_0 l_2}, k_{1f} = \frac{S_{mp} P_{f10} k_{s1}}{(k_{1f} + k_{r2}) l_6 y_0 l_2}.
\]

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**Fig.3.** Block diagram with transfer functions of the complete system (controller + barometric corrector + air flow rate corrector)
For a controller with both of the correctors, the (13)-lever equation results overlapping (15) and (21)-
equations, which leads to
\[
\left( r^2 s^2 + 2\omega_0 T_s s + 1 \right) y = k_{1p} \bar{P}_R - k_{2p} P_p -
- k_{1f} \bar{P}_f - \left( k_{1f} \bar{P}_f - k_{1f} \bar{P}_t \right);
\]  
(23)
this equation will replace the (6)-equation in the
mathematical model (equations (1) to (10)), so the
block diagram with transfer functions looks like the
one in fig.3.

4. About system’s quality
System’s behavior was studied comparing the step
responses of a basic controller and the step response
(same conditions) of a controller with correctors.
Fig. 4 presents the step responses for: a) system with
basic controller; b) system with controller and baro-
metric corrector, when the engine’s regime is kept
constant and the flight regime receives a step
modifying. The differential pressure \( \bar{P}_d \) becomes
non-periodic, but its static error grows, from -0.1% to
0.77% and changes its sign. The profiled needle
position \( y \) becomes clearly periodic, with a
significant override, more pulsations and a much
bigger static error (1.85%, than 0.2%). The most
important output parameter, the engine’s speed \( n \), has
the most important changing; more precisely, it tends
to become non-periodic (or to reduce the override),
its static error decreases, from 1.1% to 0.21% and
becomes negative.
However, in spite of the above described output
parameter behavior changes, the barometric corrector
has realized its purpose: to keep (nearly) constant the
engine’s speed when the throttle has the same
position and the flight regime (flight altitude or/and
speed) significantly changes.
Fig. 5 presents system’s behavior when the air flow

Fig.4. Comparative step response between a) basic controller b) controller with barometric corrector

Fig.5. Comparative step response between a basic controller and the same controller with air flow rate corrector
rate corrector assists the controller’s operation. In fig. 5.a is depicted the system step response for the secondary output parameters (differential pressure $p_d$ and profiled needle displacement $\bar{y}$); the differential pressure keeps its periodic behavior, but the profiled needle’s displacement tends to stabilize non-periodic, which is an important improvement. The main output non-dimensional parameters, the engine’s speed $\bar{n}$ and the combustor’s temperature $T_3^{\ast}$ have suffered significant changes, as fig. 5.b shows; both of them tend to become non-periodic, their static errors (absolute values) being smaller (especially for $\bar{n}$) and the time of stabilization has been reduced (nearly half of the initial value of the non-assisted controller). So, the flow rate corrector has transformed the system, eliminating the overrides (potential engine’s overheat and/or overspeed) and the result is a non-periodic stable system, with acceptable static errors (5.5% for $\bar{n}$ and 3% for $T_3^{\ast}$) and acceptable response times (5 to 12 seconds).

Conclusions

The object of this paper was the analyzing of some specific methods to improve the quality of a fuel injection controller, especially for the regimes or the situations when the main output parameters have unsatisfactory behaviors.

The barometric corrector is simply built, consisting of a two capsules; its integration into the controller’s ensemble is also accessible and its using results, from the engine’s speed point of view, are definitely positives; new system’s step response shows an improvement, the engine’s speed having a smaller static error and a faster stabilization when the flight regime changes. However, an inconvenience occurs, short time vibrations of the profiled needle (see fig. 4.b), curve $\bar{y}(t)$, without any negative effects above the other output parameters, but with a possible accelerated actuator piston’s wearing out.

The air flow rate corrector, in fact the pressure ratio corrector, is not so simply built, because of the drossels diameter’s choice, co-related to its membrane and its spring elastic properties. However, it has a simple form and simple and reliable parts and its operating is safe, as long as the drossels and the mobile parts are not damaged.

Air flow corrector’s using is more spectacular, especially for the unstable engines and the engines assisted by periodic-stable controllers (as fig. 5.b shows); system’s quality changes, its step response becoming non-periodic and its response time becoming significantly smaller.

Both of correctors could be used for other fuel injection controllers and/or engine speed controllers, if one chooses an appropriate integration mode and appropriate design parameters.

References: