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# CONTROL SYSTEM FOR A SINGLE SPOOL JET ENGINE WITH VARIABLE-AREA EXHAUST NOZZLE

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***Abstract:*** *This paper presents an aircraft single-spool jet engine with variable-area exhaust nozzle as controlled object. The authors have identified a possible control structure based on two input parameters (fuel flow rate* $Q_c$ *and nozzle's exhaust area* $A_5$*), respectively two output parameters (speed* $n$ *and combustor gas temperature* $T_3^*$*). One has defined an engine control system structure and one has also established its mathematical model, based on some previous contributions and experimental works (having as subject a VK-1-type jet engine). Some simulations, concerning engine's step input response, were performed, in order to establish engine's quality. The employed method and some of the obtained results could be extended for further studies (such as twin spool jet engines, or jet engines with afterburning).*

***Keywords:*** *jet engine, spool, nozzle, control, model, speed, temperature.*

## 1. INTRODUCTION

The engines for modern aircraft, especially the ones for combat aircraft, must assure high level of thrust, low time response and maneuverability. For an engine high thrust level, there are necessary high compressors pressure ratios $\pi_c^*$, high combustor burned gas temperatures $T_3^*$, as well as alternative thrust augmentation methods (such as afterburning, compressor or combustor water injection).

Aircraft jet engines as controlled objects are studied in [7,9,10], where the authors have identified, amongst a multitude of parameters, possible control parameters (inputs), possible controlled parameters (outputs), as well as theoretical command laws.

As input parameters, one has identified only three: a) the combustor fuel flow rate $Q_c$ (for all engine types); b) the exhaust nozzle's opening $A_5$ (only for engines with variable-area nozzles); c) the afterburner fuel flow rate $Q_p$ (only for the engines with afterburning).

Jet engines for aircraft are built in a large range of performances and types (such as single- or double-spool, single jet or twin jets, with or without afterburning). Different types of fuel pumps assure their fuel supply: with plungers, with pinions (toothed wheels), or with impeller. For all of them, the output fuel flow rate depends on their rotation speed and on their actuator's position; for the pump with plungers the actuator gives the plate's cline angle, but for the other pump type the actuator determines the by-pass slide-valve position (which gives the size of the discharge orifice,

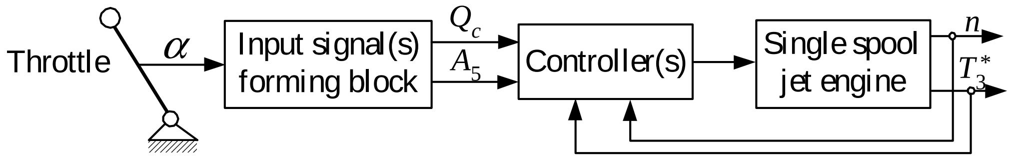

Figure 1. Engine control scheme

that means the amount of the discharge fuel flow rate).

Usually, fuel pumps are included in the jet engine's control system; more precisely: the fuel pump is turned round by the engine's shaft (obviously, through a gear box), so the pump speed is proportional (sometimes equal) to the engine's speed *n*, which is the engine's most frequently controlled parameter. So, the other pump control parameter (the plate angle or the discharge orifice width) shall be issued by the engine's speed controller [2,11].

Engine's speed controllers are built based on various operating principles, in a large range of types. Mostly all of them are controlling the engine speed using as main parameter the injected fuel flow rate [2,9,10,11,12].

Engine's exhaust nozzle's opening control systems are presented in [4,10,13], being designed as follower systems (in order to reproduce the desired $A_5$ with respect to the throttle's position.

This paper's aim is to build a model for a single spool jet engine with two input parameters, based on previous theoretical and/or experimental control schemes.

## 2. ENGINE'S CONTROL SCHEME

Single spool jet engine's most important outputs (controlled parameters) are [6,7,9,10]: spool (shaft) speed (also called engine speed) $n$ and combustor hot gases temperature $T_3^*$. As inputs (control parameters), one can use the fuel flow rate $Q_c$ and the nozzle's gas exhaust area $A_5$. Possible mixed control schemes, using the above-mentioned parameters, are presented in [9,10]. Although, the aircraft's pilot has at his disposal only the throttle (as possibility to control the engine). Consequently, the throttle has to generate somehow, by its displacement, the input signals forming, which means that engine input parameters $Q_c$ and $A_5$ should be determined as some other control systems' outputs (as figure 1 shows).

Combustor gases temperature $T_3^*$ is very difficult to be measured and to be used as control/controlled parameter; instead of $T_3^*$ nowadays jet engines' measured temperature is the more accessible $T_4^*$ temperature, behind the turbine. Even so, the gas temperature is rarely used as controlled parameter, at most as limited parameter, its control being accomplished by a distinct system, involving the injection fuel flow rate;

This paper deals with an embedded control system for a single-spool jet engine with variable-area nozzle. Engine's control system is depicted in figure 2 and consists of two sub-systems: the first one is meant to establish the injection fuel flow rate, the second one (a follower system) is meant to co-relate the exhaust nozzle's area to the throttle's position.

The first sub-system is the engine speed

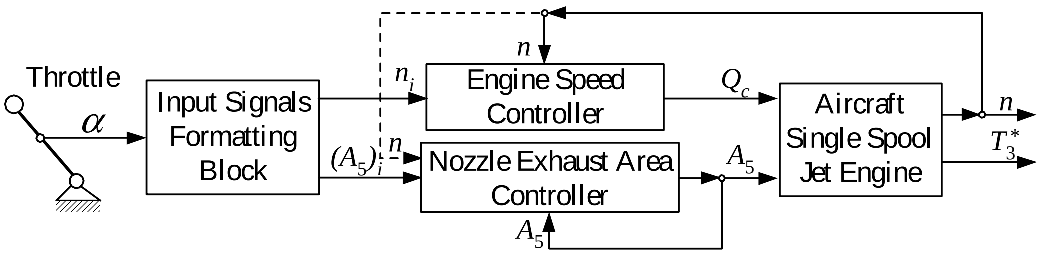

Figure 2. Single spool jet engine control system scheme

control system; such controllers were described in [2,11,12]. The second sub-system, for the nozzle's area control, is a follower-one, described in [13] (or similarly in [4] and [10]).

The system in figure 2 can be improved, for its operational security, if one uses a temperature controller (a system which discharges a fraction of the injected fuel flow rate when the highest admissible $T_3^*$ or $T_4^*$ temperature value is overflowed)

An operational block-diagram of the described system is the one in figure 3.

## 3. SYSTEM'S MATHEMATICAL MODEL

The above described system is built-up of three main parts: the engine, the speed controller and the exhaust nozzle's controller; their reunited motion equations are building the system's mathematical model.

3.1 **Jet engine's model**, determined and described in [7], consists of two equations, one for the engine's speed, the other for the combustor's temperature, both of them with respect to the fuel flow rate and to the exhaust nozzle's area, as follows

$$(\tau_m s+1)\overline{n} = k_c\overline{Q}_c + k_{nA5}\overline{A}_5 - k_{HV}\,\overline{p_1^*}, \quad (1)$$

$$\begin{aligned}(\tau_m s+1)\overline{T_3^*} &= k_{T3c}(\tau_{Tc}s+1)\overline{Q}_c + \\ &+ k_{TA5}(\tau_{TA}s+1)\overline{A}_5 - k_{TH}(\tau_{Tp}s+1)\overline{p_1^*},\end{aligned} \quad (2)$$

where $\tau_m$ is the engine's time constant, $\tau_{Tc}$, $\tau_{TA}$, $\tau_{Tp}$ – model time constants, $k_c, k_{nA5}$, $k_{HV}$, $k_{T3c}, k_{TA5}, k_{TH}$ – gain co-efficient.

The terms containing $\overline{p_1^*}$ are describing the flight regime disturbances effects.

3.2 **Engine speed controller's model**, determined and described in [11], consists of

a) fuel pump's equation (with respect to its speed $n$ and to its actuator position $y$)

$$\overline{Q}_c = k_{pn}\overline{n} + k_{py}\overline{y}, \quad (3)$$

b) actuator's equations

$$\overline{x} = k_u\overline{u} - k_{es}\overline{n}, \quad (4)$$

$$\tau_s s\overline{y} = \overline{x} - \overline{z}, \quad (5)$$

c) rigid feed-back equation (for $z$)

$$\overline{z} = \rho_s\overline{y} \quad (6)$$

where $\tau_s$ is the actuator's time constant, $k_{pn}$, $k_u, k_{es}$ – gain co-efficient, $\rho_s$ – feed-back gain.

**3.3 Exhaust nozzle controller's equations**, as determined in [13], with respect to throttle lever's position ($\theta$) and to the supplying pressure ($p_g$) are, as follows

$$\overline{A}_5 = k_{5y}\overline{y}_A, \quad (7)$$

$$\overline{y}_A = \frac{(\tau_{u\theta}s+\rho_\theta)\overline{\theta} + (\tau_{ug}s+\rho_g)\overline{p}_g}{(\tau_{yA}s+1)(\tau_{uA}s+1)}, \quad (8)$$

where the above annotations have the forms presented in [13].

Together with the above-mentioned eight equations, one has to consider both input signals formatting block's equations

$$\overline{\theta} = k_{\alpha\theta}\overline{\alpha}, \quad (9)$$

$$\overline{u} = k_{\alpha u}\overline{\alpha}, \quad (10)$$

(where $\alpha$ is the engine throttle's position angle, $k_{\alpha\theta}, k_{\alpha u}$ – gain co-efficient) and hydraulic supply equations. As shown in [9,10], the hydraulic pump is connected to the

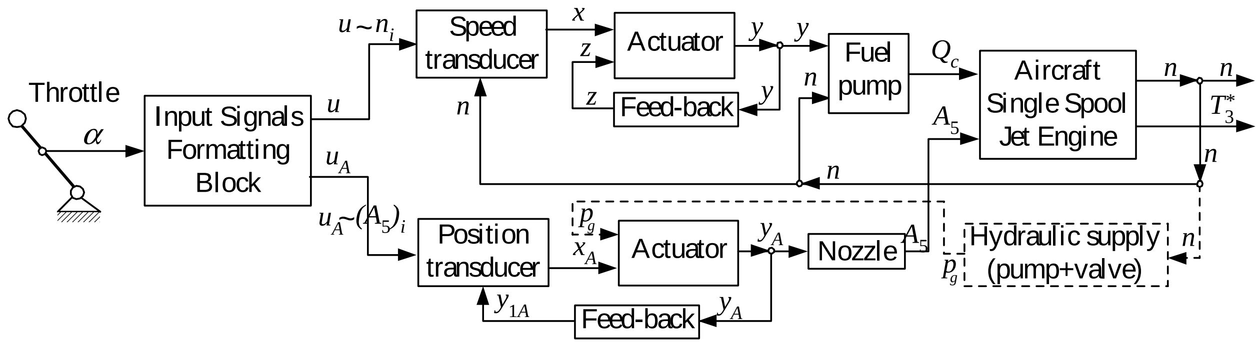


Figure 3. Single spool jet engine control system's operational diagram

engine's shaft, so its speed is proportional to $n$, so the hydraulic fluid's pressure is

$$\overline{p_f} = k_f \overline{n}. \quad (11)$$

Even if one uses for supplying a constant pressure valve, one shall consider the valve's equation, as determined in [10]

$$\overline{p}_g = \frac{k_{gf}}{\tau_g s + 1} \overline{p_f}. \quad (12)$$

Based on these 12 equations, one has built the block-diagram with transfer functions, depicted in figure 4.

## 4. ABOUT SYSTEM'S QUALITY

One can observe that the embedded control system, when the flight regime is kept constant, has a unique input, which is the throttle's position (displacement) $\alpha$. The authors have performed some simulations, in order to determine the system's response for a step input of the throttle's displacement, using the system's block diagram with transfer functions, depicted in figure 4. System's response, that means its time behavior, concerning the speed $n$ and the combustor gas temperature $T_3^*$, was studied for the embedded system, comparative to a system without variable area nozzle.

Engine transfer function was calculated as presented in [7, 10].

In the first case, the authors have simulated the time behavior for an engine (VK-1F) with variable area exhaust nozzle, at sea level, operating at maximum regime. One has considered a constant flight regime, so the terms containing $\overline{p}_1^*$ became null. System step response is presented in figure 5; one can observe a stable behavior, more precisely a non-periodic stability, for both output parameters. The engine can be considered a static controlled system, its stabilization being realized with static error(s), during a time period of 3.0…3.5 seconds. Both parameters have about the same static error, somewhere around 4.5%.

The second studied case has considered the same engine, without variable-area nozzle, so the terms containing $\overline{A}_5$ became also null. System step response is presented in figure 6; one can observe the same non-periodic stability for the engine's speed parameter $\overline{n}$, but temperature's parameter $\overline{T_3^*}$ has a different behavior, having an initial jump, a small overflow and, eventually, a non-periodic stabilization. System's static errors have, obviously, the same values, being around 4.5%; the stabilization time is a little smaller, being between 1.5 and 2 seconds.

Third case of the simulation has considered both system inputs (throttle's displacement and flight regime). More specific, one has considered the first case study configuration and, supplementary, a step growth of the inlet air pressure $\overline{p}_1^*$ (a more intense flight regime). One can observe, as figure 7 shows, a different

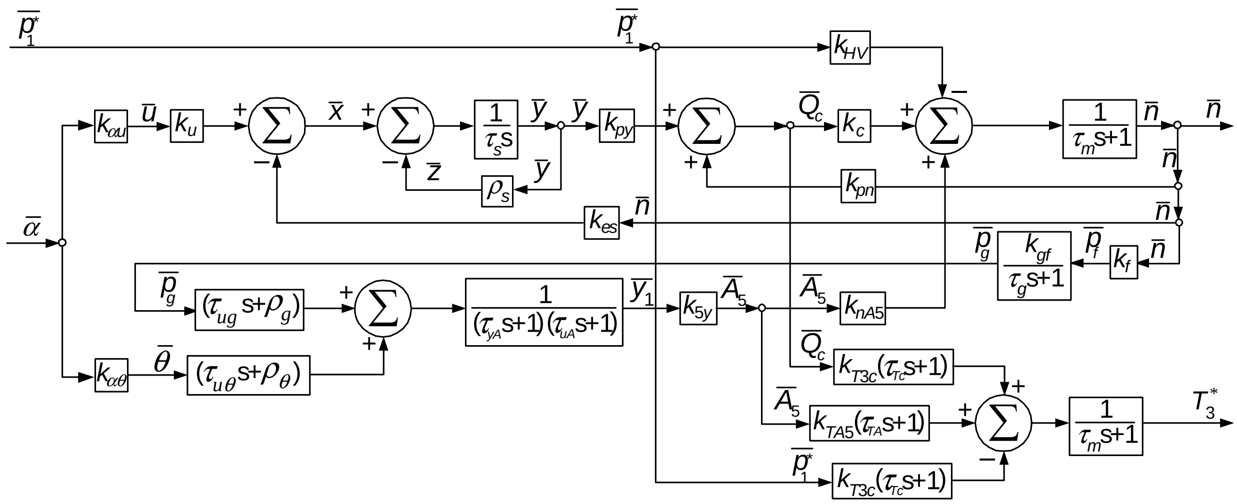


Figure 4. Single spool jet engine control system's block diagram with transfer functions

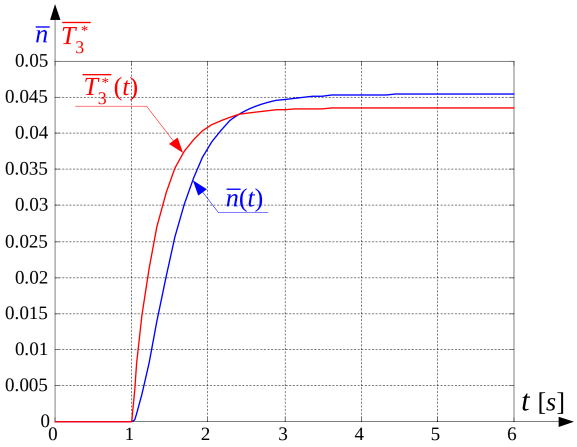


Figure 5. Time response of a single spool jet engine with variable-area nozzle for $\alpha$ step input

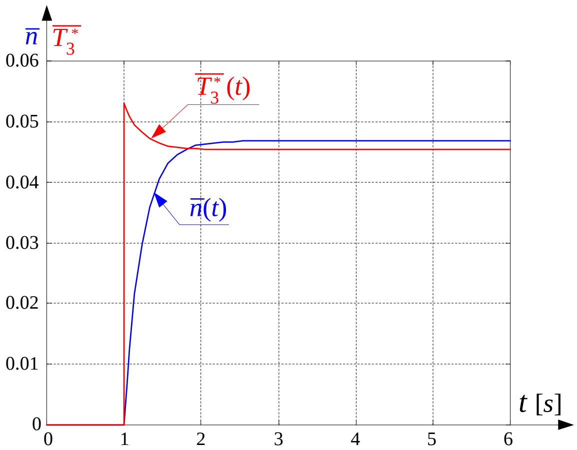


Figure 6. Time response of a single spool jet engine with constant area nozzle for $\alpha$ step input

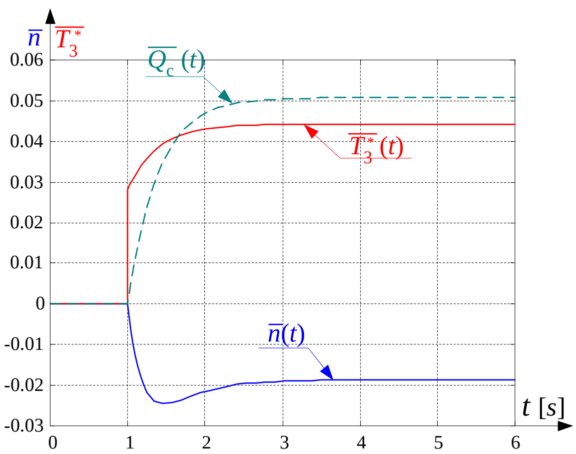


Figure 7. Step response for both inputs

(throttle $\overline{\alpha}$ and flight regime $\overline{p}_1^*$)

system behavior, concerning both parameters and their monitored aspects (stability type, static error and time of stabilization). Therefore, when the flight regime becomes more intense (flight speed increases and/or flight altitude decreases), because of the engine's speed controller design, speed parameter $\overline{n}$ should remain constant [10,11]; although, its stabilization to a new regime realizes, periodic-type, with a small initial overflow and with a small negative static error (-1.8%).

One can also observe that, in order to keep the same speed level, as well as the same thrust, the fuel flow rate has to grow (as the dashed curve in figure 7 shows); meanwhile, as consequence, the combustor's temperature parameter $\overline{T_3^*}$ level grows too, with an initial step growing, followed by an aperiodic stabilization; the static error is nearly the same (positive, around 4.5%). The stabilization times remain practically the same as in the first case.

## 5. CONCLUSIONS

The authors have studied a single-spool jet-engine (VK-1 type), with variable-area exhaust nozzle and mixed control system.

The studied embedded control system was described both as mathematical model and as block diagram with transfer functions; based on it, one has performed some simulations, in order to determine system's quality (time behavior for step input(s)).

The simulations results have shown a stable system, no matter were the studied situation. Although, comparing figure 5 and 6, one can affirm that the engine with variable-area exhaust nozzle has nearly the same behavior as the same engine with constant area nozzle, from the speed's parameter point of view; the difference is made by the combustor temperature, which has a jump and an overflow in the second case. One can affirm that the exhaust variable area nozzle's presence improves the system's behavior from the temperature's point of view.

The above-presented mathematical model and the block diagram with transfer functions can be formally used for other similar single-spool single-jet engines, being necessary the co-efficient calculus (co-efficient involved in eq. (1) to (12), having the forms determined in the referenced papers).

The same mathematical model can be completed with the appropriate equations, in order to make it useful for a study of a single spool single jet engine with afterburning, or it can be extended, with appropriate chosen modifications, to the twin spools jet engines.

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