IOP Conf. Series: Materials Science and Engineering **302** (2018) 012058 doi:10.1088/1757-899X/302/1/012058

# Correction of Dynamic Characteristics of SAR Cryogenic GTE on Consumption of Gasified Fuel

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**Abstract:** When the gas turbine engines (GTE) NK-88 were developed for liquid hydrogen and NK-89 for liquefied natural gas, performance of the systems with a turbo-pump unitary was improved and its proved without direct regulation of the flow of a cryogenic fuel, which was supplied by a centrifugal pump of the turbo-pump unit (TPU) Command from the "kerosene" system. Such type of the automatic control system (SAR) has the property of partial "neutralization" of the delay caused by gasification of the fuel. This does not require any measurements in the cryogenic medium, and the failure of the centrifugal cryogenic pump does not lead to engine failure. On the other hand, the system without direct regulation of the flow of cryogenic fuel has complex internal dynamic connections, their properties are determined by the characteristics of the incoming units and assemblies, and it is difficult to maintain accurate the maximum boundary level and minimum fuel consumption due to the influence of a booster pressure change. Direct regulation of the consumption of cryogenic fuel (prior to its gasification) is the preferred solution, since for using traditional liquid and gaseous fuels this is the main and proven method. The scheme of correction of dynamic characteristics of a single-loop SAR GTE for the consumption of a liquefied cryogenic fuel with a flow rate correction in its gasified state, which ensures the dynamic properties of the system is not worse than for NK-88 and NK-89 engines.

## 1. Introduction

Aviation gas turbine engines operating on cryogenic fuel have a number of significant advantages. Therefore, this research area became more popular in recent years [1-3]. However, when creating such kind of engines, there are problems associated with the selection of a schematic diagram of the fuel supply and the control system, ensuring the required dynamics of the SAR. The usage of cryogenic fuel in GTE necessarily assumes to be in gasified state, which leads to delay in the functioning of SAR [4]. If the heat exchange-gasifier (HEG) enters into the motor control loop, the delay has a negative effect on the quality of the regulation [5-7]. The use of cold resources of cryogenic fuel for oil cooling of the lubrication system of GTE supports in the fuel, oil cooler further increases the delay in the system, which can leads inability to provide the required indicators for stability and speed. Single-loop systems with direct control over the flow of cryogenic fuel are quite acceptable either with a small delay in maintenance, or with permissible long transient processes. When using this type of a circuit, the required acceleration time is less than 10s on the above engines.

The use of gasified fuel consumption for the regulation of gas turbine engines is possible in two ways. The first method is based on regulating the consumption of a gas dispenser, which can be carried out if there is any sufficient gasified fuel involves the installation of the receiver of a large volume. Such scheme has been successfully implemented at the domestic main gas turbine engine GTE [8]. The second method involves correction in the flow of cryogenic liquefied fuel at the expense of its gasified state. The second method can allow us without making significant changes in the system to improve the stability and performance of SAR engine.

In the practice of operating complex SAR, including with delay links, cascaded control is often used when an internal loop with a static regulator is introduced, and its controlled by an external primary circuit [9,10]. The introducing of an internal circuit with an additional adjustable parameter can significantly improve the quality of transient processes [6]. Corrective local feedbacks are used to compensate for the inertia involved in the internal circuit of the elements, which makes their use often preferred [11, 12]. The additional introduction of the relaxation circuit in the rigid feedback loop of the internal circuit, corresponding to the introduction of a speedup element, also contributes to improving the quality of regulation [10]. This article explains the detailed mathematical model of SAR GTE with regulation of the consumption of cryogenic fuel, and also the possibility of improving the dynamic quality of the system by the flow rate correction in its gasified state and its proved successfully.

## 2. Frequency characteristics of the high-pressure rotor and gas turbine heat exchanger as control objects

Theoretical and experimental studies of the NK-88, NK-89 engine systems are shown that the high-pressure rotor (HPR) and HEG can be described by the fourth-order degree transfer functions [7]. To simulate the dynamic processes in the SAR GTE, the transfer functions of the HPR and HEG, consists of series aperiodic links:

$$W_{HEG}(s)=\frac{\Delta\bar{m}_g(s)}{\Delta\bar{m}_l(s)}=\frac{1}{(T_{1HEG}s+1)(T_{2HEG}s+1)^3}; \qquad (1)$$

$$W_{HPR}(s)=\frac{\Delta\bar{n}_{HPR}(s)}{\Delta\bar{m}_g(s)}=\frac{1}{(T_{1HPR}s+1)(T_{2HPR}s+1)^3}, \qquad (2)$$

where $\Delta\bar{m}_g$, $\Delta\bar{m}_l$ - are the relative changes in the flow rate of gasified and liquefied cryogenic fuel; $\Delta\bar{n}_{HPR}$ - relative change in the rotational speed of the gas turbine engine GTE; $s$ - an operator in the Laplace transform; $T_{1HEG}$, $T_{1HPR}$ - is the time constants of the HEG and HPR of GTE respectively and characterizes their inertial properties; similarly $T_{2HEG}$, $T_{2HPR}$ - is the time constants of HEG and HPR of GTE respectively and characterizes their delay. Moreover, the component of the delay HEG is Several times greater than that of the HPR GTE and this relationship is determined in the frequency tests of engines [6].

The time constant values of the GTE HEG (1) and HPR (2) at the maximum regime are: $T_{1HEG}=0.4\,s$; $T_{2HEG}=0.044\,s$; $T_{1HPR}=0.44\,s$; $T_{2HPR}=0.01\,s$. Figure 1 shows the characteristics of logarithmic amplitude-frequency $20\cdot\lg|W_{HEG}(\omega)|$, $20\cdot\lg|W_{HPR}(\omega)|$ and phase-frequency $\arg W_{HEG}(\omega)$, $\arg W_{HPR}(\omega)$ respectively for HEG and GTE high pressure HPR, here $\omega$ represents angular frequency of oscillation, $j=\sqrt{-1}$.

Frequency characteristics analysis is shown in Figure 1 and it is clear that the influence of the component of the delay of the heat exchanger will be much more higher. Moreover, as the oscillation frequency increases the delay.

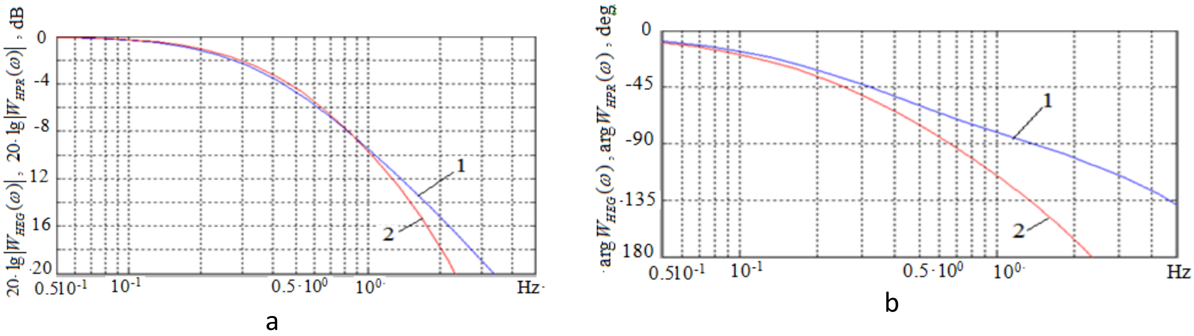



**Figure 1.** The logarithmic amplitude-frequency (a) and phase-frequency characteristics (b) of the objects of regulation: 1 - the high pressure rotor GTE; 2 – heat exchange-gasifier GTE.

So at 0.8 Hz the negative phase shifts are for the HPR - $74^0$, for the HEG -$101^0$, that is less for $27^0$, and for the frequency 2 Hz - accordingly less for $64^0$.

## 3. Model SAR GTE with direct regulation of the consumption of cryogenic fuel and correction of its consumption in the gasified state

The presence of HEG in a closed SAR GTE, naturally, worsens its stability and speed with the direct regulation of cryogenic fuel (prior to its gasification). Improving the quality of system regulation can be achieved by correcting the regulator (dispenser) of the liquid flow of cryogenic fuel $\dot{m}_l$ by its consumption in the gasified state $\dot{m}_g$ , that is, by introducing a correcting circuit (Figure 2

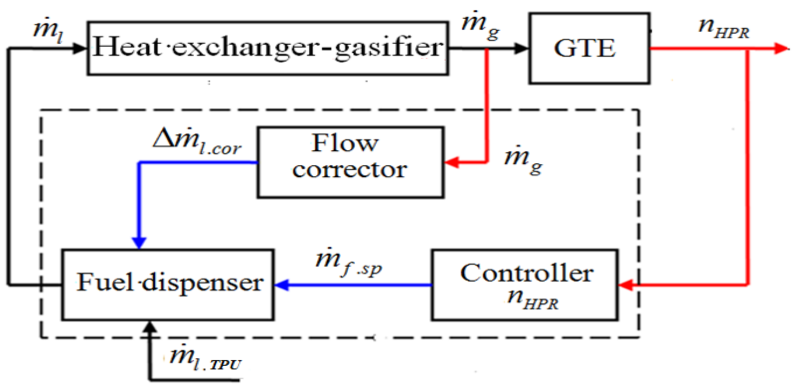
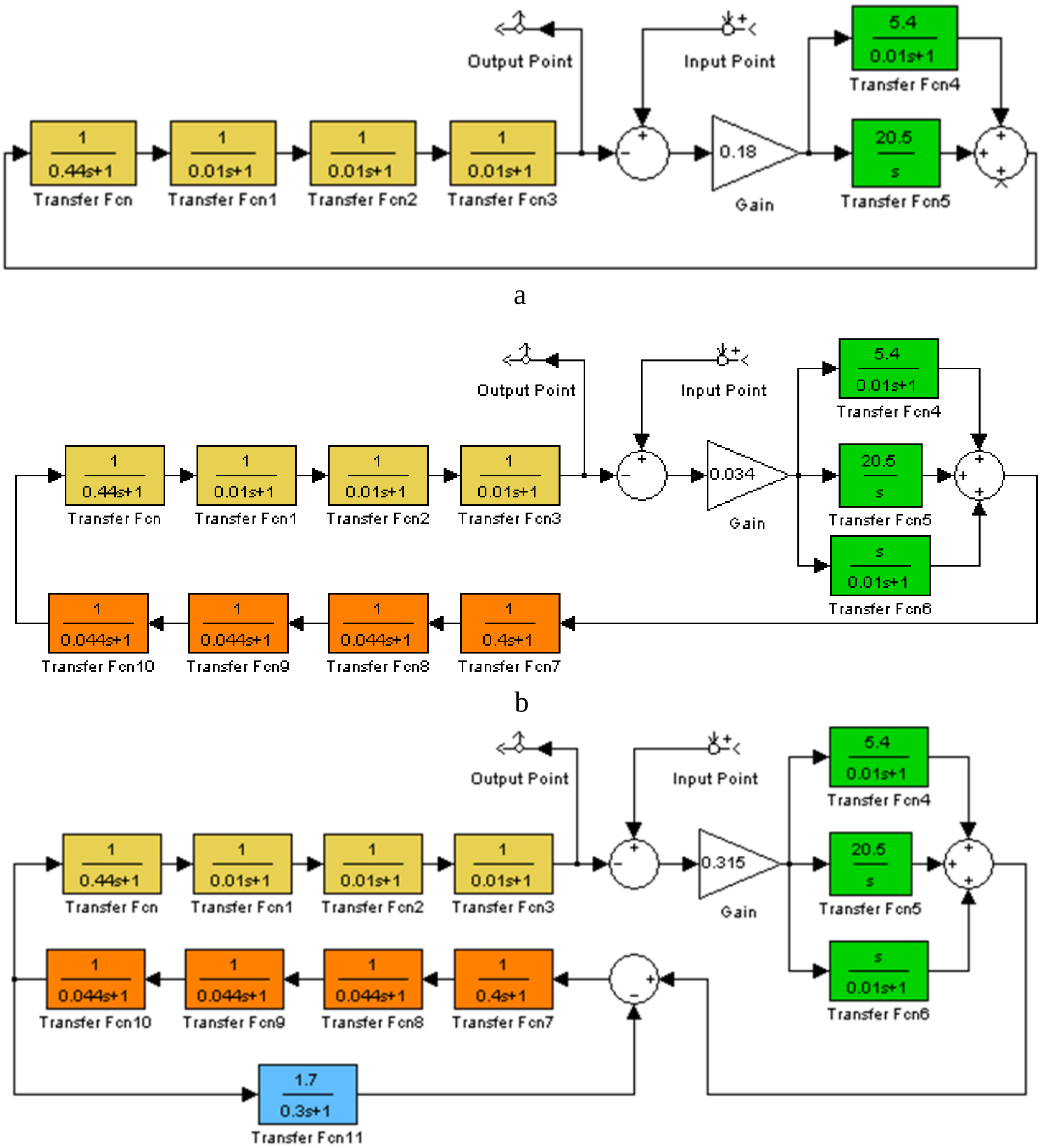



**Figure 2**. Functional diagram of the two-loop SAR GTE with correction of the cryogenic liquid fuel consumption $\dot{m}_l$ over its gasified state $\dot{m}_g$ .

Modeling of dynamic processes in SAR GTE was conducted in three variants. The first option (a) is a basic SAR with the regulation of the flow rate of kerosene PI-controller GTE. The second option (b) is SAR with single-loop flow control of a cryogenic fuel PID-regulation. The third option (c) dual-circuit system with flow control, cryogenic fuel PID-regulation and correction of the flow rate in the gasified condition. This corrector is represented by a periodic link with a gain of 1.7 and the time constant 0.3 s.

Figure 3 shows the indicated different variants of the structural diagrams of the SAR GTE control blocks are made by using the simulation software MATLAB/SIMulink [13].




c

**Figure 3.** Structural diagrams of the GTE SAR for modeling in the software package MATLAB / SIMulink: a - basic SAR with the regulation of kerosene flow by the PI-controller; b - with an adjustment of the flow rate of the liquefied cryogenic fuel by the PID-controller; c - with the regulation of the flow rate of the liquefied cryogenic fuel by a PID-controller with correction for its consumption in the gasified state, ● - HPR; ● - HEG; ● - controller; ● - fuel consumption corrector.

## 4. Analysis of the efficiency of a correcting characteristics of a cryogenic gas turbine engine with respect to the gas consumption of a fuel

The parameters of the gas turbine controllers for all variants and the flow corrector in the third variant are selected in such a way that the overshoot of the HPR speed is 5 %. Figure 4 shows the parameters of the transient process with a single step-like action. As it can be seen in Figure 4, reaching 95 % of the regulated parameter in a single-loop cryogenic SAR with direct regulation of the cryogenic fuel occurs 4 times slower with respect to the basic "kerosene" system (2.76 s and 0.68 s).

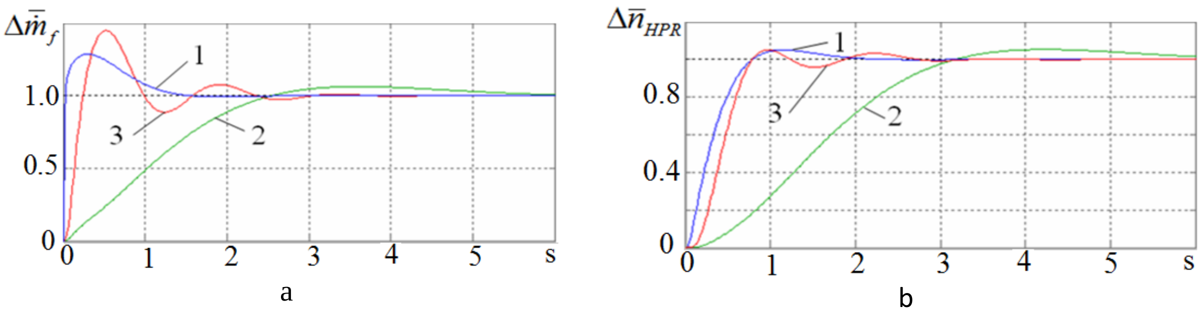



**Figure 4**. Transient processes in the SAR GTE on fuel consumption (a) and on the rotation frequency of the HPR (b): 1 - basic system with the regulation of kerosene flow PI-controller; 2 - single-loop system with regulation of the flow of liquefied cryogenic fuel by a PID-controller; 3 - a system in the regulation of the flow rate of a liquefied cryogenic fuel by a PID-regulator and correction for the consumption of cryogenic fuel in the gasified state.

In a system with direct control of the flow rate of the cryogenic component by a PID-controller and correction by the consumption of gasified fuel, the transient process is close to the process in the base system. The time to reach the specified control parameter with a deviation not more than 1 % has the same tendency of 1.93 s in the base system, 6.0 s in the single-circuit system and 2.6 s in the system with the PID-controller and correction for the gasified fuel consumption.

## 5. Conclusions

A scheme for correcting the dynamic characteristics of an aircraft GTE with the regulation of the flow rate of a liquefied cryogenic fuel by a PID-controller and correcting for its consumption in a gasified state is proposed. As a result of simulation of dynamic processes in SAR, it has been established that when the internal correcting circuit is introduced for the consumption of gasified fuel and the use of the PID-controller, the system performance is significantly increased. The duration of the transient in SAR with correction is more than three times less than the duration of a single-loop system with regulation of the consumption of liquefied fuel.

**Nomenclature:**

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| $\dot{m}$ | mass flow |
| $n$ | shaft speed |

**Indices:**

| | |
|---|---|
| g | gas |
| l | liquid |
| f | fuel |
| cor | correction |

**Abbreviations:**

| | |
|---|---|
| GTE | the gas turbine engines |
| HEG | the heat exchange-gasifier |
| HPR | the high pressure rotor |
| SAR | the system of automatic regulation |
| TPU | the turbo-pump unit |

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