Power plant control system operation during changing spacecraft position

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Abstract

Nowadays the necessity in small spacecraft (SC) with total mass up to 1000 kg is increased. In order to control such SC it is necessary to have electric rocket power plants, which should satisfy to many requirements: lifetime, mass, thrust, specific impulse. They should be controlled in thrust wide range over prescript low (for example, harmonically). Analysis of real electric rocket thruster (ERT) usage (in particular, plasma-ion thrusters (PIT) and stationary plasma thruster (SPT)) is represented in this report.

Introduction

The devices requiring super-small accelerations (about $10^{-6} \dots 10^{-5}$ m/s^2) for their operation will be placed on some small SC. Small value of micro-acceleration permits to overcome some physical phenomena, spoiling technological processes and to use completely molecular forces and electrophores, which are intended to improve technological processes for precise materials creation. It is evident, that such technology usage onboard the SC is reasonable rather if it is necessary to obtain absolutely unique results, or if economic efficiency is required[1].

1. Thruster's selection

We analyzed if it is possible to use two type of the ERT for examined problem[2]. First of all we examined PIT with diameter 50 mm. Such thruster exhausting velocity ~35 km/s is able to create thrust up to $2 \dots 8 \cdot 10^{-3}$ N. Secured lifetime of such thruster type is ~10^4 hours. PIT tests showed that it is possible to modulate thrust, varying ion beam current under action of prescribed low of acceleration potential U_1 on the emission electrode (fig. 1). Correlation between control action (acceleration potential U_1) and output parameter (thrust) was examined during the experiment.

Secondary, we analyzed SPT. Such ERT widely used in SC technology. Thruster with diameter of acceleration channel 50 mm, with thrust $0.5 \dots 1.5 \cdot 10^{-3}$ N and exhausting velocity ~11 km/s was analyzed. Estimated lifetime of such thruster - ~$3 \dots 5 \cdot 10^3$ hours. SPT were controlled over thrust due to some peculiarities in the discharge chamber processes. Propellant feeding and discharge potential variations were examined as control action. Satisfactory results were obtained only at small frequencies down to 20 Hz. For SPT it is practically impossible to increase frequency if we control propellant flow rate.
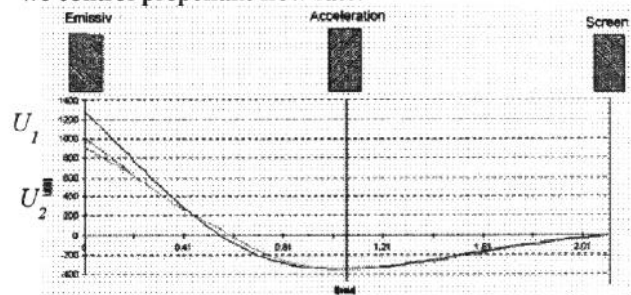

Fig.1

So we select PIT- 50 as an object for investigation. PIT-50 power processing unit (PPU) was changed. The main changes were done in power supplying source of the emission electrode (fig. 2). Control system is oscillation generator (G), power amplifier (M), transformer (Tr1) and rectifier (VD1-VD4) with filter. At PPU output we obtain single-pole pulse signal with duplicate frequency of the generator's signal. One of the main problems is how to integrate thruster with transformation system and control system. It occurs if it is necessary to secure high dynamic performances of process stability[3].
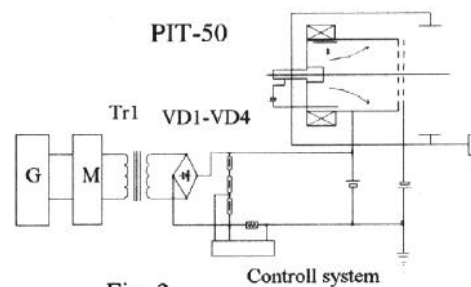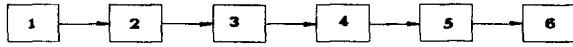

Fig. 2

Fig 3

One can represent ERT as not closed structural scheme (fig. 3), where 1 - power supplying source, 2 - potential transformer, 3 - transformer, 4 - rectifier, 5 - filter, 6 - power plant.

General differential equation, describing transition processes in the mentioned circuit, can be obtained by different ways. For example, it is possible to find equation for every link and then using initial conditions, obtain dynamical performances of the whole system. This method is very huge and uncomfortable. Method of transition function based on operation method for equation formation is used more frequently.

As a result of transformation we obtain the following dependences:

$$W_{system} = \frac{U_{output}}{U_{input}} = K_c \frac{1 + pT_1^{'} + pT_2^{'}}{1 + pT_1 + p^2T_2 + p^3T_3 + p^4T_4 + p^5T_5 + p^6T_6}$$

$$U_{outup}(t) + \sum_{n=1}^{6} T_n \frac{d^n U_{output}}{dt^n} = K_c \left(U_{input}(t) + T_1^{'} \frac{dU_{input}(t)}{dt} + T_2^{'} \frac{d^2 U_{input}dU}{dt^2} \right)$$

This equations are the initial one rather for analysis of this system stability or for ERT characteristic stability, in which the main processes are investigated. The main peculiarity of analyzed device is various mediums, in which process is investigated:

a) electric circuit with concentrated parameters;

b) volumetric medium (propellant feeding system, plasma, beams of charged particles).

Each of these processes is investigated separately, but there are lot of unknown in the phenomena collection and relationships between them. So, it is very important to develop PIT equivalent dynamic model, permitting to calculate PPU parameters and also to investigate some problems concerning controlling and stability in the system PPU+ERT.

Unlinear ERT resistance under first approximation can be determined with the help of static current voltage characteristic (CVC), which described by numerous of n-degree.

R_{equ}, obtained from CVC of such circuit in the case of operating power plant will depends on I_{magnet}; $U_{discharge}$, U_{source}, $U_{intermediate}$ and so on.

Processing lots of experimental data the regression dependencies R_{real}, $R_{intermediate}$ and $R_{discharge}$ are mutually connected and also connected with $R_{equivalent}$, this system solution is very complicated. Solving this

system, it is necessary to take into account connections between ERT structure and PPU, which are represented in fig. 4.
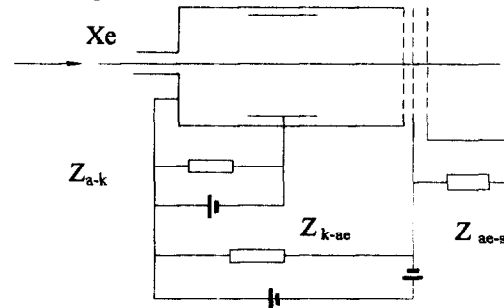

Fig.4

Where z_{a-k} - impedance between anode and cathode; z_{k-ae} - impedance between cathode and acceleration electrode z_{ae-s} - impedance between acceleration electrode and screen.

From PIT scheme one can see that ERT elements is connected with PPU by $z=f(R, L, C)$ dependence. Solving these equations system it is possible to obtain the initial transition dependence and to determine this system stability.

Lets assume ERT as a collection of non-linear resistances, connected by some way. Gas discharge chamber (GDC) and system of acceleration and deceleration are displaced by non-linear resistances, which are calculated with the help of CVC.

The calculation algorithm is following. GDC power supplying system, beginning with switching on moment, is calculated. Then basing on this calculation the transition GDC equivalent resistance is determined.

The numerical results are used in the system of acceleration. In this case we assume, that last systems have been switched off to the moment of GDC switching on, and their selves - transition processes have been finished. So, calculating the system of acceleration the non-zero initial conditions are used. Besides we took into account GRC transition processes. So, R_{ERT} can be represented by the following way:

1. $R_{ERT} = U_r/I_u = R = const$;

2. $R_{ERT} = f(U_p; U_{np}; U_{нст}; I_m)$ multi-parametrical static regression dependencies;

3. $R_{ERT} = \left\{ \begin{array}{c} -\dfrac{U}{I} \\ -\dfrac{dU}{dI} \end{array} \right\}$ from static CVC;

4. $R_{ERT} = f(U_p; U_{np}; U_{нст}; I_m; t)$ multi-parametrical dynamic regression dependencies;

5. R_{ERT} taking into account non-zero initial conditions;

6. $R_{ERT} = f(U^{'}; t)$, where U' – is written taking into

account ignition discharge;

7. $R_{ERT} = f(U';t)$, where U' – is written taking into account covering oscillations;

8. $R_{BRT} = f(U;I;t)$.

2. How to determine PIT frequency performance

The main part of the investigation is how to determine possible boundary of thruster's control. It is possible to estimate this boundary with the help of PIT transition processes time. Practically the time of single transition process is about $1.5...3 \cdot 10^{-3}$ sec (fig. 5), that is equivalent to oscillations with frequency 660-670 Hz, i.e. this result is confirmed PIT stable operation under frequencies less than 600 Hz. Operating in these ranges of frequencies the potential break number is decreased and thruster's operational stability is increased greatly. If "parasitic" capacity and induction are increased this frequency value is decreased and it is the reason of PIT unstable operation
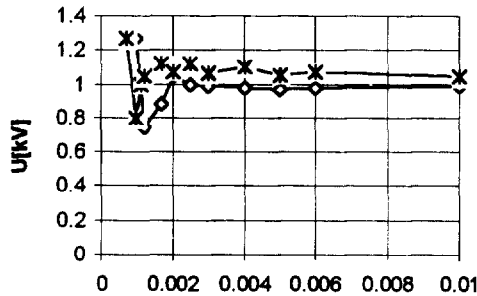

t[s]

Fig. 5

Source performances and oscillograms were measured during the experiments. For amplitude frequency performance (AFP) representation, the dependence of Fourier decomposition spectrum amplitude on frequency was used. AFP shows very clear on which frequencies in the initial signal the main energy is and where the resonance and auto-resonance areas of analyzing system are.

In order to make easier the processing of the obtained data, lets give the equation in undimensional form:

$$\bar{U}_{input} = U_{input}/U_0 \; ; \; \bar{P}_{output} = \bar{U}_{output} = U_{output}/U_1;$$

where constant values are the following: $U_0 = 1000$ V;

$U_1 = 5$ V. From this we can obtain: $\bar{W}_{system} = \dfrac{\bar{P}_{output}}{\bar{U}_{input}}$

In fig. 6 only qualitative results of input and output system signals are represented. In this case the signal with frequency 100 Hz have been made. From fig. one can see that power plant responsed with carrying frequency of 100 Hz and with insignificant drop
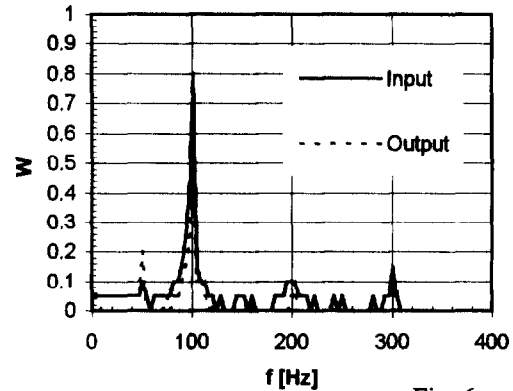
on bottom frequencies.

Fig. 6

Conclusions

1.   The value of PIT control range is 50-600 Hz (assuming bottom limit of control is in the limits 10-15 Hz).

2.   Using the preliminary analysis it is determined how PIT can be used in the system of stabilization and for the purpose of micro-acceleration decreasing.

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