Research and optimization of the hydraulic performance of bench lines for testing of low thrust spacecraft engines

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Abstract. Low thrust engines perform important functional tasks in control systems of motion, orientation and stabilization of spacecraft on various paths and space orbits. They are subject to high-reliability and long operating time in pulsed modes with a large number of starts. Bench tests of the engines are a special part of the program development of low thrust engines with high reliability and efficiency. The article analyses wave processes in hydraulic lines of test benches, which prevent obtaining reliable parameters and performances of engines during tests. Authors show that the exclusion of oscillation processes in test bench systems is the main condition for the organization and planning of tests. Similarity conditions for bench hydraulic lines of spacecraft propulsion systems are developed. A methodology for estimating the frequency responses of the bench lines during pulsed test modes is presented. Mathematical functions of geometric parameters of the bench hydraulic lines on the pulse responses of low thrust engines are obtained, allowing optimization of the bench propellant feeding system to avoid resonance oscillation processes. Research results provide reliable estimates of the parameters and reliability of low thrust engines.

1. Introduction

Low thrust engines (LTE) are designed for spacecraft motion control on space paths, spacecraft stabilization, orientation and correction in space. Design features of the LTE defined by their special mass and dimensions characteristics, specific processes of mixing and combustion of propellant components, absence of regenerative cooling of the engine chamber. They may operate in continuous and pulse modes and the design of LTE provides for multiple firings with varying durations (from several hundredths of a second to tens of seconds). The total number of cycles of LTE can amount to as many as one million starts, with the active life of a spacecraft up to 15 years.

A specific feature of LTE is the non-stationarity of its operating mode. When the engine thrust is increased at build-up time and reduced at cut-off time, the mixing, combustion and exhaust processes take place under off-nominal conditions, engine efficiency is significantly reduced. The specific impulse in such modes is lower than in continuous modes: \( J_{\text{non-stat mode}} < J_{\text{cont mode}} \); its reduction can reach up to 50% [1].

The energy parameters and thermal condition of the LTE during its operation are determined by factors whose influence cannot often be determined by theoretical calculations. In these cases, only experimental studies make it possible to make a final choice of the optimum rocket propellant mixing schemes and parameters, design of units and the engine configuration as a whole. It should be noted that...
nowadays there is no acceptable theory of experimental testing of complex technical systems to optimize the design parameters and other characteristics of rocket-space technology products [2].

2. Research task
In the process of designing experimental (prototype) development of LTE for various applications, much attention is paid to bench testing methodology, technical equipment of benches simulating the impact of physical conditions in space and the use of diagnostic methods and equipment for various physical investigations and measurements.

The requirements for firing tests benches of LTE are specific, the main of which are: to achieve the required high-altitude environment; to compliance with the laws of variation of engine inlet pressures and combustion chamber pressures, ensuring that the temperature of the propellant components is within the specified limits (both negative and positive).

The dynamic processes occurring in the propellant lines depend on many factors. It is known [3, 4, 5] that the type of dynamic processes in lines has a significant influence on engine parameters, which is especially relevant for LTE, as operation in pulse modes, causing dynamic processes, is one of the most typical features of operation of such engines. It is therefore necessary to ensure that the dynamic processes occurring in the test bench lines are consistent with those in the propellant lines of propulsion system in order to reliably determine the performance of the engine during the test run.

A simple solution to this problem only by the identical design of the propellant feeding system for LTE on the bench and in the propulsion, system does not appear to be possible for a number of reasons:

- the need for a high degree of safety in bench testing, which requires sufficient distance between the supply tanks and the vacuum chamber;
- the possibility of implementing various test programs on the test bench, which is possible due to the installation of additional fittings (valves, throttling devices and measuring instruments) in the propellant line;
- design features of the test bench.

Popov and other authors considered the task of velocity propagation when viscous fluid velocity increases in a circular pipe under effect of suddenly appeared constant differential pressure [6, 7, 8]. Solutions to the Navier-Stokes equation are obtained for an incompressible fluid assuming that the velocity distribution is determined beyond the section where the flow stabilises along the length of the pipe. As the friction, effects propagate towards the pipe axis, the unevenness of the velocity distribution increases and the velocity profile asymptotically approaches parabolic.

In order to realize the condition of similarity of hydrodynamic processes it is necessary to ensure similarity of boundary and initial conditions, on which solutions of equations depend. Initial and boundary conditions are determined by the values of pressure \(p\) and flow velocity \(c\) at the initial moment of time and the patterns to be satisfied at the end sections of the tube during the non-stationary process.

An analysis of the equations of fluid flow in a circular pipe show that hydrodynamic similarity of propellant lines in the propulsion system and on the test bench is achieved by compliance of the numbers in the equations: \(St = idem, Eu = idem, Fr = idem\) and \(Re = idem\), as well as equality of Mach number \(M = C/a\) (where \(a\) is reduced speed of sound in system "line - liquid"), dimensionless wave resistance \(\Delta = p c a / p^2\) and relative friction losses \(\Delta p / p^\ast\). It is also necessary to ensure that the hydraulic lines and boundary conditions on which the solutions to the equation depend are geometrically similar.

Therefore, the similarity conditions are criteria that should be the same for the test bench and the propulsion system at a specified propellant components flow rate \(\dot{m}\).

The task of oscillations of a viscous incompressible fluid is considered in a number of papers [6, 8, 9]. Solutions to this problem show that the law of influence on the fluid flow significantly affects the distributions in non-stationary flows. Therefore, when modelling non-stationary hydrodynamic processes, it is very important to ensure the identity of the type and mode of the processes, in addition to compliance with the similarity criteria. For the purpose of mathematical models, fluid flow is
described by equations in cross sectional averaged flow but time-dependent variables. By means of this hydraulic method, a one-dimensional mathematical description of fluid flow is obtained. In which quasi-stationary coefficients are used, having at each moment in time the values obtained by steady-state motion of the medium at velocities equal to the instantaneous velocities. It is noted in [9] that the use of quasi-stationary coefficients does not lead to significant errors in calculations of non-stationary hydrodynamic processes in the case where the distribution of velocities over the flow section over time is not significant.

Two types of equation solutions are used when analysing the wave performance of lines: for forced oscillations of the system, which give the frequency response, and for free oscillations, which define the transient motion of the system.

A special feature in the creation of test bench lines for feeding propellants into the engine under pulsed mode conditions with a frequency \( f \) is the matter of the natural frequency of oscillation of the fluid in the line \( f_0 \). The natural (free) oscillations in a system arise after the termination of the action of external disturbances. The free oscillations, and first of all the frequencies of these oscillations, are of interest for explanations of the peculiarities of the dynamical performances of the system.

It is obvious that at \( f_0 \approx f \), processes will be initiated in the test bench lines, which will significantly affect the performance of the tested liquid propulsion system, which will inevitably lead to unreliability of the engine parameter estimates based on the test results.

3. Optimise the performance of the bench’s hydraulic lines

The pulsed modes of LTE generate turbulent and non-stationary flow processes of the propellant components in the lines. The features of non-stationary flows in lines are discussed in [7, 8]. The dynamic operations occurring in the propellant lines depend on many factors, determined by the properties of the propellants, the design of the lines and the sequence of the LTE [10]. The nature of non-stationary processes is particularly influenced by the inertial properties of the fluid at small cross-sections and long line lengths [6, 11].

Optimisation of firing test processes for LTE requires solving the task of ensuring identity of the propellant supply system for LTE including compliance of inertial, wave and hydraulic performance of feeding lines.

Therefore, the basic criteria for optimising the performance of the test bench lines to obtain reliable information on the functional capability of LTE based on the results of fire tests should be formulated as follows:

- the propellant flows in the bench and spacecraft lines should be similar;
- the oscillating processes resulting from the pulsed operation of the engine to be tested does not have to introduce additional errors in the evaluation of the performance of the engine.

Similarity conditions of hydrodynamic processes occurring during non-stationary flow of an incompressible fluid could be described by means of the equations of flow and continuity of the fluid [12].

The proximate use of differential equations leads to considerable and usually insurmountable difficulties in solving specific tasks. The complexity of the problem of calculating turbulent currents is caused by the fact that turbulent currents are non-stationary, with changes in magnitudes over time having the character of a multitude of pulsations of different frequencies and amplitudes. The paper [9] states that the coefficients of the equations could be expressed using known numbers:

\[
\text{St} = \frac{f}{\Delta t} \quad \text{Strouhal} ; \quad \text{Eu} = \frac{\rho^*}{\rho C_s^2} \quad \text{Euler} ; \quad \text{Re} = \frac{C_L \nu}{\mu} \quad \text{Reynolds} ; \quad \text{Fr} = \frac{v^2}{gL} \quad \text{Froude}
\]

where \( \rho \) and \( \nu \) are density and kinematic viscosity of the fluid.

Equation of dynamics of the test bench line supplying the propellant component to the engine is written in the form:
\[ f \cdot \frac{dm}{dt} + \xi \cdot \frac{p c^2}{2} = p_{in} - p_{out} + p_m, \]

(1)

where \( f = l/F \) is the inertial loss coefficient; \( l \) is the length of the line section; \( F \) is the cross-sectional area of the line section; \( m \) is the rate of fluid flow; \( p_{in} \) and \( p_{out} \) are inlet and outlet pressures of the line section; \( p_m \) is the pressure of the mass load of the liquid column on the area \( F \); \( \xi \) is the hydraulic resistance coefficient.

The hydraulic resistance coefficients for steady and non-stationary flow of the fluid have different values. The steeper the front of the liquid flow rate is rising at time and the higher the frequency of oscillation of the flow parameters, the greater the difference of these values. However, the hypothesis of equality of friction coefficients for steady and non-stationary modes is used in the study of dynamic modes in hydraulic systems with low-viscosity fluids [13, 14].

The practice of mathematical modelling [15, 16] shows that most tasks of low-frequency dynamics (up to \( \approx 20 \) Hz), including those related to investigation of fluid motion in bench hydraulic lines, can be described with a sufficient degree of accuracy by simple dependences if we consider a system with lumped parameters. In this case the length of the line subdivision section \( l_{max} \) could be an order of magnitude smaller than the wavelength of the highest process frequency \( f_{max} \) taken into account in the calculations. Taking the speed of propagation of longitudinal waves in a liquid \( v_{long} = c \), and considering that the wavelength \( \lambda_{long} = c/f \), we can write:

\[ l_{max} \leq \frac{2\pi a}{\omega_{max}n} = \frac{a}{f_{max}n} \]

(2)

where \( n \) is the safety factor; \( n \leq 6 \ldots 12 \).

The paper [8] notes that the hydraulic resistance of the line causes only a slight reduction of the resonance frequencies.

The resonance frequencies have the values below:

\[ f_p = \frac{1+2n}{4\pi} \left( \frac{E_{liq}}{\rho_{liq}} \right)^{1/2}, \]

(3)

where \( n = 0,1,2 \ldots ; \ c = \left( \frac{E_{liq}}{\rho_{liq}} \right)^{1/2} \) is the velocity of propagation of disturbances in the line (speed of sound); \( l \) is the length of line.

In order to avoid the phenomenon of resonance causing negative (in terms of influence on the test results) non-stationary processes, the natural frequency of the lines must be significantly different from the frequency of forced response excited by the pulse operation of LTE being tested. The following frequency dependence \( f_0 \) of the maximum frequency of forced response \( f_{eng \ max} \) is assumed, taking into account the safety factor \( f_0 \geq f_{eng \ max} \).

Using the safety factor \( n = 10 \), we obtain \( f_0 = 10 \cdot f_{eng \ max} \), and then we write formula (3) like this:

\[ l_{bench \ max} = \frac{0.1a_{\infty}}{\pi f_{eng \ max} (2 + \frac{2D}{\delta})^{1/2} \cdot \frac{E_{liq}}{E_{line}}} \]

where \( l_{bench \ max} \) is the maximum length of the bench line.

As the value of \( a_{\infty} \) is significantly greater than \( \beta_t \), i.e. given the inequality \( a_{\infty} \gg \beta_t (T - T_0) \), we can write:

\[ l_{bench \ max} = \frac{0.1a}{\pi f_{eng \ max} (2 + \frac{2D}{\delta})^{1/2} \cdot \frac{E_{liq}}{E_{line}}} \]

(4)

In the paper [13] dependence of optimum length of the line \( l_{line} \) and wavelength \( \lambda_{long} \) of the highest frequency of the process of forced longitudinal oscillations \( l_{line} = 0.1 \cdot \lambda_{long} \) is given. Using the
dependence $\lambda_{\text{min long}} = a/f_{\text{max}}$, where $a$ is the speed of sound of the liquid, write the equation for the design of bench lines:

$$l_{\text{bench}} \leq \frac{0.1a}{f_{\text{eng max}}} \text{ or } l_{1\text{bench max}} = \frac{0.1a}{f_{\text{eng max}}}.$$ (5)

Thus, a restriction is defined: the length of the test bench line could be such that its natural frequency is at least 10 times the maximum frequency of LTE pulse mode during testing [17]. Considering the two conditions for the maximum length of the bench line, it should be noted that the permissible value will be the one that satisfies the condition:

$$l_{\text{allowable bench}} = \min(l_{\text{bench max}}, l_{1\text{bench max}}).$$ (6)

Based on the mathematical equations and conditions obtained, it is possible to calculate design values for the lengths of the bench lines for the conducted tests of LTE, ensuring reliable values of the test results.

4. Conclusion
On the basis of the conducted research and based on the results of scientific works of other authors, possible methods of conducting tests of LTE with simulation of operating conditions of engines in the propulsion systems of spacecrafts are presented.

The analysis of features of pulse modes of operation of LTE as part of spacecraft defining the requirements to the design of special test equipment of hydraulic systems of the bench, the mechanisms of influence of these modes on the reliability of the results of bench tests at design development of the engine were investigated.

A method of estimating the frequency responses of the hydraulic lines of a test bench for LTE during pulse modes is presented.

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