UDC 629.7.036.54-63:662.61:534.83

Siberian Journal of Science and Technology. 2017, Vol. 18, No. 3, P. 558–566

THE ALGORITHM FOR ESTIMATING RESERVES OF THE WORKING PROCESS STABILITY IN COMBUSTION CHAMBERS AND GAS GENERATORS OF LIQUID ROCKET ENGINES

V. I. Biryukov[1], V. P. Nazarov[2*], R. A. Tsarapkin[1]

[1]Moscow Aviation Institute (National Research University)
4, Volokolamskoe highway, Moscow, 125993, Russian Federation
[2]Reshetnev Siberian State University of Science and Technology
31, Krasnoyarsky Rabochy Av., Krasnoyarsk, 660037, Russian Federation
[*]E-mail: Nazarov@sibsau.ru

The experimental evaluation of the working process stability with respect to acoustic oscillations in combustion chambers and gas generators of liquid rocket engines is one of the main methods used in rocket engine construction. External and internal disturbing devices using explosive hexogen often lead to the damage to the fire walls and structural elements of the aggregates The disadvantages of traditional external impulse devices also include a considerable wide range of the pressure pulses values generated by them in the combustion chamber with the same value of the sample of the explosive and with the constant parameters of the atmosphere in the combustion chamber, which is due to the scatter of the explosives characteristics. An alternative approach is proposed for creating a pulse effect on the working process in the combustion chamber by exploding an electrical conductor. The disturbing device is made with an explosive chamber connected by a channel with the reaction volume of the combustion chamber. In the electro-impulse disturbing device a thin wire fastened to isolated electrodes is used instead of the charge of the explosive. As a substance used to create a pressure pulse, this generator uses gas filling the blasting chamber, the mass of which depends on the pressure in the combustion chamber and in the chamber of the electro-impulse perturbative device. If one immediately heats this gas to a temperature of several thousand degrees, one can get a gas that is close in parameters to the combustion products of explosives in traditional external impulse devices. Such heating can be carried out by discharging through a wire of an electric capacitor charged to several thousand volts. First, instantaneous (for several microseconds) evaporation of the wire, and then through the plasma channel formed at the site of the wire, the final discharge of the capacitor takes place, with virtually all of the energy stored in the capacitor discharged. The plasma temperature in this case, according to different sources, can reach from several tens of thousands to one million degrees. The gas is also heated by adiabatic compression with a shock wave. The metal particles formed after the evaporation of the wire and the condensation of the vapor have a value of several nanometers and, therefore, do not damage the inner layer of the combustion chamber. The methodological bases are considered and the algorithm for estimating the stocks of stability to acoustic vibrations from the reaction of the combustion process to such pulsed artificial disturbances is developed. There have been developed electro-impulse disturbing devices that reduce the risk of damage to the components of liquid rocket engine assemblies in full-scale and model test, and have an obvious prospect for widespread use.

Keywords: liquid rocket engine, acoustic oscillations, disturbing device, electric explosion of conductors, damping decrement, intercorrelation function.

Сибирский журнал науки и технологий. 2017. Т. 18, № 3. С. 558–566

АЛГОРИТМ ОЦЕНКИ ЗАПАСОВ УСТОЙЧИВОСТИ РАБОЧЕГО ПРОЦЕССА В КАМЕРАХ СГОРАНИЯ И ГАЗОГЕНЕРАТОРАХ ЖИДКОСТНЫХ РАКЕТНЫХ ДВИГАТЕЛЕЙ

В. И. Бирюков[1], В. П. Назаров[2*], Р. А. Царапкин[1]

[1]Московский авиационный институт (национальный исследовательский университет)
Российская Федерация, 125993, г. Москва, Волоколамское шоссе, д. 4, А-80, ГСП-3
[2]Сибирский государственный университет науки и технологий имени академика М. Ф. Решетнёва
Российская Федерация, 660037, г. Красноярск, просп. им. газ. «Красноярский рабочий», 31
[*]E-mail: Nazarov@sibsau.ru

Экспериментальная оценка устойчивости рабочего процесса по отношению к акустическим колебаниям в камерах сгорания и газогенераторах жидкостных ракетных двигателей является одним из основных методов, применяемых в ракетном двигателестроении. Внешние и внутренние возмущающие устройства, использующие взрывчатое вещество гексоген, нередко приводят к повреждению огневых стенок и элементов конструкции агрегатов. К недостаткам традиционных внешних импульсных устройств следует также отнести значительный разброс величин генерируемых ими импульсов давления в камере сгорания при одинаковой величине *навески взрывчатого вещества и при постоянстве параметров среды в камере сгорания, что, по-видимому, связано с разбросом характеристик взрывчатых веществ. Предложен альтернативный подход создания импульсного воздействия на рабочий процесс в камере сгорания путем взрыва электрического проводника. Возмущающее устройство выполнено со взрывной камерой, соединённой каналом с реакционным объёмом камеры сгорания. В электроимпульсном возмущающем устройстве вместо навески взрывчатого вещества используется закреплённая на изолированных электродах тонкая проволочка. В качестве вещества, используемого для создания импульса давления, в этом генераторе используется заполняющий взрывную камеру газ, масса которого зависит от давления в камере сгорания и в камере электроимпульсного возмущающего устройства. Если мгновенно нагреть этот газ до температуры в несколько тысяч градусов, можно получить газ, близкий по параметрам к продуктам сгорания взрывчатых веществ в традиционных внешних импульсных устройствах. Осуществить такой нагрев можно путём разряда через проволочку заряженного до нескольких тысяч вольт электрического конденсатора. При этом сначала происходит мгновенное (в течение нескольких микросекунд) испарение проволочки, а затем через образовавшийся на месте проволочки плазменный канал происходит окончательная разрядка конденсатора с выделением практически всей накопленной в конденсаторе энергии. Температура плазмы при этом, по разным источникам, может достигать от нескольких десятков тысяч до миллиона градусов. Осуществляется также нагрев газа при адиабатическом сжатии его ударной волной. Образующиеся после испарения проволочки и конденсации паров частицы металла имеют величину нескольких нанометров и поэтому не повреждают внутреннюю оболочку камеры сгорания. Рассмотрены методические основы и разработан алгоритм оценки запасов устойчивости к акустическим колебаниям по реакции процесса горения на такие импульсные искусственные возмущения. Разработаны электроимпульсные возмущающие устройства, которые снижают риск повреждения составных частей агрегатов жидкостных ракетных двигателей при натурных и модельных испытаниях и обладают очевидной перспективой для широкого применения.*

Ключевые слова: жидкостный ракетный двигатель, акустические колебания, возмущающее устройство, электрический взрыв проводников, декремент затухания колебаний, взаимокорреляционная функция.

Introduction. All produced combustion chambers and gas generators of liquid rocket engines (LRE) have to be experimentally tested on the stability of the working process with the respect to high-frequency pressure fluctuations in these components in the range of ±10 % of their nominal modes [1].

The main task in evaluating the stability of the working combustion process is to determine, with the smallest number of experiments, the tendency of rocket engine components to maintain the instability of combustion and thus to develop measures to suppress it. Another task solved by the methods of stability evaluation is to determine the effectiveness of various means of stabilizing the working process, such as anti-pulsation partitions and acoustic absorbers [2; 3]. Unfortunately, there are no principal means of ensuring the sustainability of the working process. Thus, we always need some relative evaluations of the effectiveness of the chosen method of stabilizing the working process in the developed LRE. Using the experimental methods [1–3] of the stability evaluation, it is possible to determine the most critical mode of oscillations, susceptible to resonant interaction with the combustion process, and to take the necessary measures to suppress it. In addition, the methods of evaluating stability stocks allow us to investigate the effect of changes in the structural elements of engine components and various parameters of the working process on the stability of combustion [1–3]. At present, the evaluation of the stability of the working combustion process in LRE is carried out by introducing a pulse of pressure from the external device into the reaction volume of the combustion chamber through the channel in its wall [1; 3–12]. As a source of pressure in these external impulse devices (EID), a necessary amount of explosive (E) – hexogen, isolated from the channel by a metal membrane [1; 3; 12–14] is used. When the explosive charge is exploded, the fragments of such a membrane can damage the bronze inner shell of the combustion chamber, deform the blast nozzles, etc. In this regard, the presence of a membrane in these devices is their disadvantage. The disadvantages of traditional EID can also include a considerable range in the values of the pressure pulses generated by them in the combustion chamber while the amount of the explosive stays the same and the parameters of the atmosphere in the combustion chamber are constant, which is apparently related to the range of the explosive characteristics, such as: its laydown thickness, the thickness of the membrane, etc. To eliminate the disadvantages of EID, it has been proposed to use an explosion of a metallic conductor of electric current (wire) when discharging a capacitor with accumulated energy of several thousand joules [4]. At present, hexogen is used as an explosive in EID, with a weight of about 0.5 to 3.5 grams in TNT equivalent. The explosion of one gram of TNT is equivalent to the energy released at the time of the wire explosion of approximately 4390 J. To release this energy, it is sufficient to charge a capacitor of 500 MkF with an electrical voltage of 4200 V to evaporate the conductor.

The development of an electro-impulse disturbing device. The disturbing device [4] is made with an explosive chamber connected by a channel to the reaction volume of the combustion chamber. In the electro-impulse disturbing device (EIDD), instead of the explosive charge, a wire (0.1–0.5 mm) is attached to isolated electrodes. As a substance used to create a pressure pulse, this generator uses the gas filling the blasting chamber, the mass of which depends on the pressure in the combustion chamber and in the EIDD chamber. Thus, for example, the mass of nitrogen, which is used to purge the DD, which fills an explosive chamber with a volume of 8 cm^3 at a pressure of 10 MPa, is ~1 g. If you immediately heat this nitrogen to a temperature of several thousand degrees, you can get a gas that is close in parameters to the products of combustion of explosives in traditional disturbing impulse device (DID). It is possible to carry out such heating by discharging through a wire of an electric capacitor charged to several thousand volts. First, instantaneous (for several microseconds) evaporation of the wire takes place, and then through the plasma channel formed at the site of the wire, the final discharge of the capacitor occurs, with the release of all the energy stored in the capacitor. The plasma temperature in this case, according to different sources, can reach from several tens of thousands to one million degrees. The gas is also heated by adiabatic compression with a shock wave. The metal particles formed after the evaporation of the wire and the condensation of the vapor have a value of several nanometers and, therefore, do not damage the inner shell of the combustion chamber. The scheme of the installation with the EIDD is shown in fig. 1.

The design of the experimental sample of a single-charged electro-impulse disturbing device [4] is shown in fig. 2.

EIDD contains the case *1* with the nipple *2* attached to it, through which a pressure pulse is introduced into the combustion chamber. In the case *1*, a cavity *3* is formed in which an electrical node *4* is mounted, which is an axisymmetric body made of a dielectric with electrodes *5* firmly fixed therein. The electrodes are retained in the insulator by means of thread bushes *6*. The insulator itself is fixed in the case *1* by means of a closing sleeve *7* and a coupling nut *8*. Between the end face of the insulator *4* and the end surface of the cavity *3*, an explosive chamber *9* is formed into which the ends of the electrodes *5* protrude. A detonating wire *10* is soldered to the ends of the electrodes *5*. In the case *1* the hole *11* with the welded fitting pipe *12* is made for blowing the explosion chamber with nitrogen. The results of preliminary studies confirm the sufficiency of the energy of the shock wave in calculating the stocks of stability of the working process in the combustion chambers of LRE in relation to high-frequency (HF) pressure fluctuations.

The algorithm for estimating stability reserves of working process as the result of the spectral processing of pressure pulsations in LRE aggregates during bench tests. The dynamics of a quasilinear system with given initial conditions and external influences is described by a system of equations for preserving the material balance, and after their linearization, the harmonic oscillator equation is obtained [2; 5–11]. Often, Laplace transforms over time variable t are applied to the equations of free oscillations in perturbations, or the change of variables $x = x = e^{\int \delta dt}$ is introduced. As a result, we obtain a nonlinear *characteristic* equation of the dynamical system, which has order one unity less than the initial one. In general, it can be represented as:

$$(\delta + p)^{n-1}\delta + b_1(\delta + p)^{n-2} + \ldots + \\ + b_{n-2}(\delta + p) + b_{n-1}\delta + b_n = 0, \quad (1)$$

here p – differentation operator,

$$p = \frac{d}{dt}.$$

The characteristic equation (1) has n roots that form *the fundamental system of solutions of the free oscillation equations* after the reverse transition to the variable x.

The case of forced oscillations of a linear dynamical system is investigated by the influence of an impulse signal on the system. Then variables mean *output* values, and external influences make *input*.

The impulse response function of the system w describes the change in the output volume from the rest state to the new state and is characterized by a change in time t and the moment of application of the pulse δ_1. The condition of physical feasibility can be formulated as

$$w(t, \delta_1) = 0, \ t < \varnothing_1. \quad (2)$$

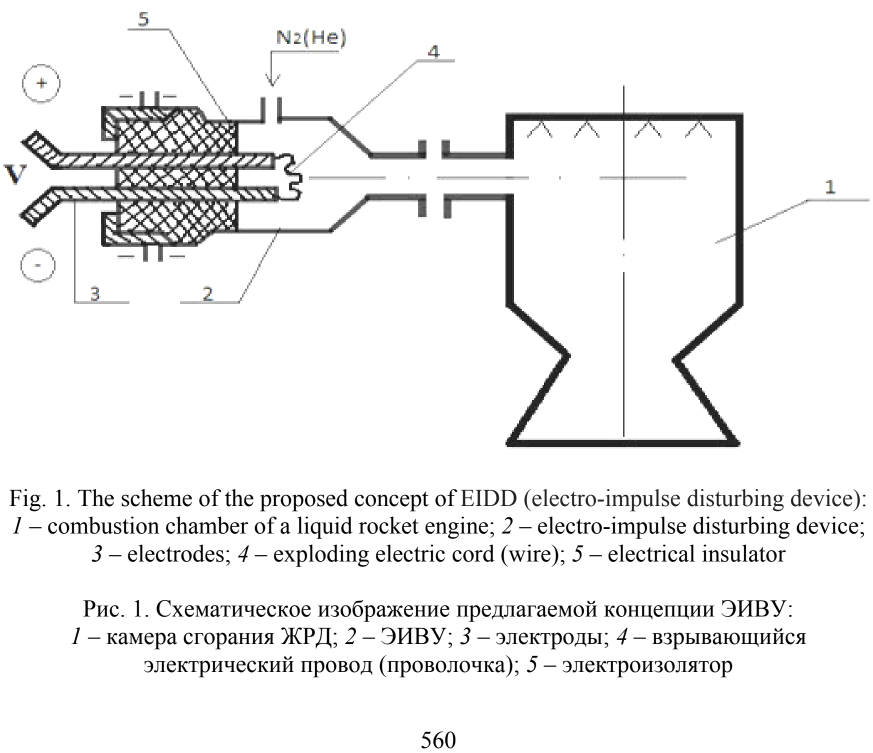

Fig. 1. The scheme of the proposed concept of EIDD (electro-impulse disturbing device):
1 – combustion chamber of a liquid rocket engine; *2* – electro-impulse disturbing device;
3 – electrodes; *4* – exploding electric cord (wire); *5* – electrical insulator

Рис. 1. Схематическое изображение предлагаемой концепции ЭИВУ:
1 – камера сгорания ЖРД; *2* – ЭИВУ; *3* – электроды; *4* – взрывающийся
электрический провод (проволочка); *5* – электроизолятор

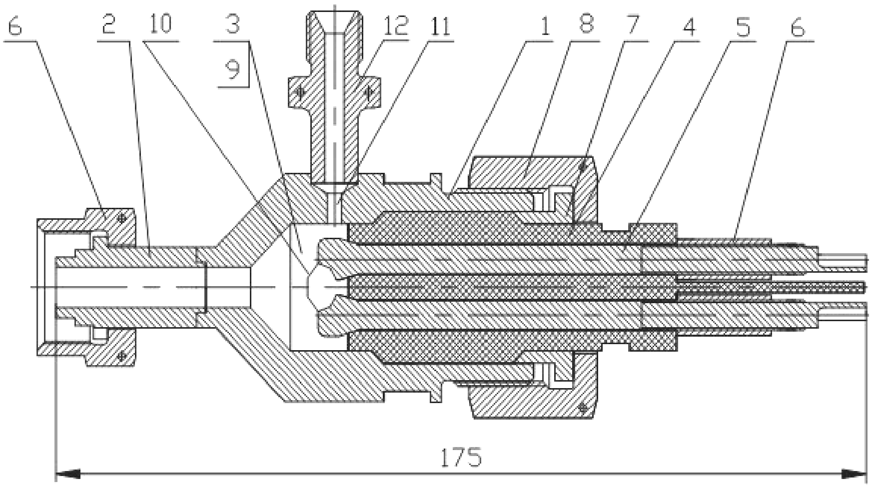

Fig. 2. The design of the pressure pulse generator (electro-impulse disturbing device): *1*, *2* – the case with a nipple; *3* – the volume for introduction of nitrogen; *4* – insulator; *5* – electrodes; *6* – thread bushings; *7* – closing sleeve; *8* – coupling nut; *9* – blasting chamber; *10* – wire; *11*, *12* – the channel and the nitrogen supply connection

Рис. 2. Конструкция генератора импульсов давления (ЭИВУ): *1*, *2* – корпус с ниппелем; *3* – объем для ввода азота; *4* – изолятор; *5* – электроды; *6* – резьбовые втулки; *7* – втулка нажимная; *8* – гайка накидная; *9* – взрывная камера; *10* – проволочка; *11*, *12* – канал и штуцер подачи азота

The transfer function W (s, t) is a function of the complex variable s and real t, related to the impulse response of the equation

$$W(s,t) = \int_0^\infty w(t, t-\tau) e^{-s\tau} d\tau, \quad (3)$$

where $\tau = t - \delta_1$.

The transfer function is meaningful only in the region of the complex variable s, where for its real part $Re(s)$ the inequality takes place

$$Re(s) > c_0$$

and at the same time the conditions are observed

$$\int_0^\infty |w(t, t-\tau)| e^{-s\tau} d\tau < \infty \text{ if } c \geq c_0. \quad (4)$$

In the theory of stationary linear systems, the transfer function is treated as the Laplace transform of the function $w(\tau)$, which is the response of the system to a unit pulse at time $t = 0$:

$$W(s) = \int_0^\infty w(a, a-\tau) e^{-s\tau} d\tau = \int_0^\infty w(\tau) e^{-s\tau} d\tau. \quad (5)$$

The transfer function of a linear stationary system is the Laplace transform from the function $w(\tau)$, which shows its response at time $t = a$ to the impulse applied earlier: $a - \tau$.

For the characteristic equation in the form of

$$\frac{d^n x}{dt^n} + b_1 \frac{d^{n-1} x}{dt^{n-1}} + \ldots + b_n x = a_0 \frac{d^m y}{dt^m} + \ldots + a_m y \quad (6)$$

such a transfer function has the following form:

$$W(s) = \frac{a_0 s^m + a_0 s^{m-1} + \ldots + a_m}{s^n + b_1 s^{n-1} + \ldots + b_n}. \quad (7)$$

The transfer function of a nonstationary system is considered similarly to the concept of a stationary system. Let the external pulse $\delta(t - u)$ act on the input of the nonstationary linear system, which is further amplified by the coefficient e^{su} (modulated complex gain), then the response of the system can be written as exp $su * w(t - u)$. Applying the superposition principle, we have:

$$\int_{-\infty}^{t} \exp(su) \delta(t-u) du = \exp st;$$

$$\int_{-\infty}^{t} \exp(su) w(t-u) du = \exp st \int_0^\infty \exp(s\tau) w(\tau) d\tau.$$

The transfer function $W(s)$ for $Re(s) > c_0$ is the ratio of $x(t)/y(t)$ in the process caused by the "action" $y(t) = \exp(st)$, see formula (6). The transfer function of a nonstationary system for a fixed time is defined as the Laplace transform with respect to the argument τ of the function describing the output quantity that is a response to a unit pulse with a delay of τ. In a nonstationary process, the difference is the dependence of the transfer function on the time t as a parameter. The transfer function of a stationary system is analytically expressed in terms of the coefficients of the oscillation equation (6). For a nonstationary system, therefore, the transfer function can not be expressed, and it is calculated only approximately [1].

There are few approaches for determining the transfer functions of dynamical systems. The methods most widely used in acoustic problems are based on the connection between the transfer function and the impulse response function, in particular the method expressing the impulse response function through the roots of the generalized characteristic equation [10; 15]. In this case, an approximate expression of the transfer function is obtained in the form of a fractional-rational function with clearly expressed poles. Another method of calculating the transfer function is to expand the impulse response function into a formal power series. The coefficients of the Taylor series are analytic functions. Both methods are applied under the condition that the oscillation equation is given in the interval $(-\infty, T)$.

The response of acoustic dynamic systems to external influences differs from the exciting force. One of the characteristics is the moment of application of the impact, which can be remote to minus infinity or finite. In this case, time start is $t = 0$.

The reaction of the system can be determined in the following cases:

– if the impulse response function of the system $w(t, u)$ is known and the external action $y(t)$, which causes a definite reaction, this reaction can be calculated using the convolution integral;

– if the external action can be transformed according to Laplace, the dependence describing the output quantity can be described using the transfer function of the system;

– if the transfer function and the "left" Laplace transform of the input action are known [15].

Also, the system response is calculated using the equation of oscillations and frequency characteristics. The latter method is applied if the frequency characteristics of the system are known. Then, when calculating the response to an external action, it is appropriate to use Fourier transforms [10].

The frequency characteristics of *non-stationary systems* are functions of two variables: frequency and time. The complex frequency response is equal to the ratio of the output value of the system or the dynamic link to the external action, if the response of the system satisfies the condition

$$\int_0^\infty \left| w(t,\ t-\tau) \right| d\tau < \infty. \tag{8}$$

If the process is considered in a finite time interval, then the oscillation equation must be defined on an infinite interval adjoining to the left. To determine the complex frequency response, it is sufficient to calculate the transfer function and make a substitution: $s = i\omega$. The task of determining the frequency characteristics of *non-stationary* systems differs from stationary by doubling of independent variables, for example, when showing characteristics graphically, which is associated with the construction of each curve for a certain time.

The experimental determination of frequency characteristics. *The frequency* characteristics of the system are defined as the characteristics of the transfer function section for the values of the argument $s = i\omega$. The complex frequency function [2; 5; etc.] is the section $C(\omega, t)$ of the transfer function $W(i\omega, t)$:

$$C(\omega, t) = W(i\omega, t). \tag{9}$$

The transfer function of a linear dynamic system or a complex frequency response, as well as a transient response, fully reflect the response of the system to external influences. Let a harmonic signal be applied to the input of the linear link

$$x = A(x) \sin \omega t,$$

where $A(x)$ is the amplitude; ω is an angular frequency of this influence.

At the output of the link at the end of the transient process, harmonic oscillations of the same frequency are represented by the dependence

$$y = A(y) \sin(\omega t + \varphi),$$

where $A(y)$ is the amplitude of the steady state oscillations; φ is the phase shift between input and output oscillations.

For a fixed amplitude of the input oscillations, the amplitude and phase of the steady-state oscillations at the output of the link are a function of the frequency of these oscillations. The analytical dependences $A(\omega)$ and $\varphi(\omega)$ are called the amplitude and phase functions. Amplitude and phase frequency characteristics are often combined into one: amplitude-phase frequency response (APFF). In this case, APFF is constructed in the complex plane, where the abscissa axis is the axis for the real part $Re\,[W]$ of the transfer function of the link, and the ordinate axis for its imaginary part $Im\,[W]$. The frequency response can be presented in exponential form. Let at the input of the linear link be a signal of the form $x = A(x)\exp(i\omega t)$, and at the output the amplitude of the oscillations changes from it and the harmonic receives a phase *shift* $y = A(y)\exp(i\omega t + \varphi)$. In general terms

$$C(\omega, t) = \left| A(\omega, t) \right| e^{i\varphi(\omega,\, t)}, \tag{10}$$

where $\left| A(\omega,\ t) \right|$ is the amplitude frequency response; $\varphi(\omega, t) = \arg F(\omega, t)$ is a phase frequency response.

The steady-state reaction of the stationary system to the considered action is also harmonic and with the same frequency. The amplitude and phase of the oscillations change. In this case, the ratio of the amplitude of the output quantity to the amplitude of the input action is equal to the value of the amplitude-frequency response (AFR) at the value of the argument, which coincides with the frequency of the action of ω. Thus, the phase shift between the output signal and the external action is equal to the value of the phase frequency characteristic of the dynamic link at a value of ω. If the oscillation equation is known, then the expression of the frequency characteristics through its coefficients is realized on the basis of formula (1) in the following form:

$$C(\omega) = \frac{a_0 i\omega^m + \ldots + a_m}{(i\omega)^n + b_1 (i\omega)^{n-1} + \ldots + b_n}. \tag{11}$$

In the case when the free oscillations of the system are undamped under some initial conditions, the frequency characteristics lose the physical meaning considered above, but the relation in the form of formula (11) with the coefficients of the oscillation equation remains valid.

The experimental determination of the frequency characteristics is based on the equality of the complex frequency response to the ratio $x(t)/y(t)$ under the external action $y(t) = \exp(i\omega t)$ and the fulfillment of the condition (11).

To do this, it is necessary that the time interval during which the process is analyzed is limited to the left and that the response to the harmonic effect of the link is also limited in an infinite time interval. In gas-dynamic experiments, as a rule, the first condition is satisfied. Suppose that condition (11) is also satisfied. Also, a necessary condition for the experiment is multiple repeatability of results in the absence of external influences, except for one specially organized harmonic effect of a given frequency from the frequency interval determined by the sensitivity of the system to harmonic effects. Let t be the time counted from the beginning of the process studied, and $[0, T]$ is the time interval at which the particular experiment (process) takes place. The initial conditions for this process should be able to vary widely. Then, in order to obtain the frequency characteristics of the system or link, it is sufficient to record changes in the output quantity in the interval $[0, T]$ in processes caused by the effects

$$y'_i(t) = a_i \cos \omega_i t;\; y''_i(t) = a_i \sin \omega_i t,\; i = 1, 2, \ldots, m,$$

for arbitrarily chosen amplitudes and frequencies from the range [Ω1, ..., Ωn] under the corresponding initial conditions. If the initial conditions for the experiment can be extended to the interval $(-\infty, 0)$, then they are computed. If the processes in the system with the coefficients of the oscillation equation frozen at the time $t = 0$ are asymptotically stable with respect to the output signal, then the option of additional definition is the assumption of stationarity of the system for $t < 0$, while the coefficients of the oscillation equation are equal to the frozen values. For example, if the external harmonic effect on the investigated link has the form $a_i \cos\omega_i t$, then the steady-state reaction is an expression

$$x(t) = a_i A(\omega_i)\cos[\omega_i t + \Theta(\omega_i)], \tag{12}$$

where $A(\omega)$ and $\Theta(\omega)$ are the amplitude and phase frequency characteristics of the stationary system used to extend the system.

Then from formula (12) it follows that

$$x(0) = a_i A(\omega_i)\cos \Theta(\omega_i), \tag{13}$$

$$d^{2k-1}x/dt^{2k-1}\big|_{t=0} = (-1)^k a_i \omega_i^{2k-1} = A(\omega_i)\sin \theta(\omega_i),$$

$$d^{2k-1}x/dt^{2k-1}\big|_{t=0} = (-1)^k a_i \omega_i^{2k} A(\omega_i)\cos \theta(\omega_i),$$

$$k = 1, 2, \ldots, \frac{n}{2}. \tag{14}$$

Another option to extend the system is to equate the coefficients of the right-hand side of the oscillation equation with zero. In this case, the frequency characteristics can not be used to obtain the response of the link to the pulse. The frequency characteristics obtained with different variants of pre-determination will be different.

For stationary systems and systems with periodically changing parameters, one can do without calculating the initial conditions, taking them into account by appropriate organization of the experiment. To do this, the frequency characteristics should be removed after the expiration of the practical attenuation of free oscillations. The reaction of the system in this case is of a steady nature, and the output value (or output signal) will vary with a period equal to the external action. The frequency characteristics of stationary systems will not depend on time, and the characteristics of systems with periodically changing parameters will depend on the time with the period of variation of the coefficients of the oscillation equation. In this case, the obtained characteristics are extrapolated on the interval of time preceding the moment of establishment of the system reaction, which is equivalent in the experiment to the input of the initial conditions in accordance with the analytical extension of definition. In combustion chambers and LRE gas generators, the effects of capacitance and inertia can vary with time and determine the tendency of the system to pulsations with some characteristic frequencies. With an external effect on the dynamic system and after its removal, the response of the system, the establishment or damping of oscillations, is characterized by its transient response. The steady-state and transient processes are determined by the complex transmission coefficient K_T, which can be represented as the ratio of the signal at the output $\hat{s}_2$ from the system to the sinusoidal signal at its input $\hat{s}_1$:

$$K_T = \hat{s}_2 / \hat{s}_1 = K_{\text{пер}}(\omega)e^{-i\varphi(\omega)} =$$

$$= Re\left|\, \bar{K}_T(\omega) \right| + iIm\left|\, \bar{K}_T(\omega) \right|. \tag{15}$$

Here $Re\left|K_{\text{пер}}(\omega)\right|$, $Im\left|K_{\text{пер}}(\omega)\right|$ are the real and imaginary parts of the transmission coefficient.

The absolute value of the transmission coefficient characterizes the reaction of attenuation or amplification of the input sinusoidal signal, and its phase determines the shift. The connection between the shape and duration of the pulse and its spectrum is realized in practice using filters with a narrow bandpass. The signal is represented as the sum of the harmonic components. The filter integrates the signal over a time interval T approximately equal to the reciprocal of the bandpass of the filter Δf. If the main process period is greater than $T = 1 / \Delta f$, then the signal spectrum at the filter output will be the same as the envelope spectrum of the signal $\hat{s}\,(t)$ at the input [10; 12; 15]. Fourier integral for large values of the period T represents the spectrum of the signal $S'(\omega)$ in the form

$$S'(\omega) = \int_{-\infty}^{\infty} s(t)e^{-i\omega t}\,dt \tag{16}$$

from here its backward transformation gives

$$s(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} S'(\omega)e^{-i\omega t}\,d\omega. \tag{17}$$

A rectangular pulse has an infinitely wide spectrum. It follows from the property of the mutual correspondence of the time function and its spectrum that the bounded spectrum can only be of a function that slowly falls to zero value with the passage of time. It is found out that in the frequency domain, where the normalized frequency is less than ½ (half-period is less than the correlation interval), the spectrum has an approximately constant amplitude, and with a further increase in frequency, the spectral amplitudes decrease rapidly to zero. It follows that the energy of the process is mainly concentrated in the frequency range from 0 to $f = 1/t_{\text{ср}}$, where $t_{\text{ср}}$ is the average pulse duration equal to the ratio of the pulse area to its amplitude.

To determine the relations between the real and imaginary parts of the transfer function, we consider the excitation of the system by the step function $\sigma_0(t)$, whose amplitude is zero for $t < 0$. The spectral density of such a function has the form

$$S'(\omega) = 1/i\omega_A. \quad (18)$$

Here $\omega_A = \omega + i\delta$, $\delta > 0$ of positive values t и $\omega_A = \omega - i\sigma$ for negative ones; δ – any small quantity.

The signal at the output of the system can be represented by a transition function or a characteristic of the system [10; 12; 15; 16]:

$$\sigma'_0(t) = \frac{1}{2\pi}\int_{-\infty-i\delta}^{\infty-i\delta}\left[\bar{K}_T(\omega)/i\omega\right]e^{i(\omega t-\varphi(\omega))}d\omega. \quad (19)$$

The way of integration can be closed in the upper half-plane for positive values of t and a semicircle in the lower plane for negative t. For a step function, the transmission factor is one. For the real system when $\omega \to \infty$, the transfer coefficient $\bar{K}_T(\omega)/i\omega(\omega) \to 0$, and its time derivative also tends to zero [15]:

$$\frac{\partial\sigma'_0(t)}{\partial t} = \int_{-\infty-i\delta}^{\infty-i\delta}\bar{K}_T(\omega)e^{i\omega t} = 0,\ t < 0. \quad (20)$$

Let the transmission coefficient be in the form $\bar{K}_T(\omega) = K_1(\omega) + iK_2(\omega)$, assuming $\delta \to 0$ and replacing t by $-t$ in formula (20), we obtain the relation between the real and imaginary parts of the transmission coefficient:

$$\int_{-\infty}^{\infty}K_1(\omega)\cos\omega t d\omega = -\int_{-\infty}^{\infty}K_2(\omega)\sin\omega t d\omega\ > 0. \quad (21)$$

If we know the real part, we can calculate the imaginary, and vice versa.

Under the assumption that the functions of four-terminal network are rational, in a number of papers [5; 6; 10; etc.] the relations between their real and imaginary parts are obtained, according to which it is easy to calculate the impedances or conductivities of the contours under study.

There are different methods for calculating the damping decrement [2; 3; 5; 6; 10; 14–16]. One of the methods measures the sweep of oscillations during one cycle and determines the time interval between the onset of the disturbance and the period of oscillation being analyzed. The operation for other time points is repeated and the amplitude variation graph in time is constructed. The slope of the *graph* of $A(t)$ characterizes the damping decrement. According to another technique, the pressure transducers are passed through a logarithmic amplifier and the amplitude levels are fixed, then the attenuation decrement is determined from the envelope of the pressure pulsations. Both methods for unfiltered pulsation readings allow us to determine the rate of attenuation of all pressure fluctuations. If it is necessary to determine the characteristics of the oscillations for a particular frequency, the pressure transducer should be passed through the filter and then the rate of damping of the oscillations is determined. For filtering, it is desirable to reproduce the signal in the reverse mode, in this case only the last 3, 4 periods of damped oscillations are distorted. The inclined straight line approximating the periodic dependence characterizes the magnitude of the damping decrement. To determine the experimental values of the vibration decrement the following methods can also be applied: spectral, correlation, amplitude and instantaneous method [1; 12]. The amplitude method and the method of the instantaneous period almost did not get used in practice. In experimental studies of the working process stability in liquid rocket engines [1; 3; 12], spectral and correlation methods were most widely used. The decrement of oscillations according to the spectral method is determined from the width of the signal power spectrum, fig. 3.

To detail the complex oscillation process in real combustion chambers, the spectral width is taken into account by means of a specific filter Δ_f of the spectro-analyzer. A three-point method is used in the algorithm [1; 3; 10; 12], and the method takes into account the dependencies of the left and right ascents, background and other interference, relative to the calculated point. At the same time, the pair of points near the maximum is searched, and a pair of those points is chosen, which yields the minimum sum of the magnitude of the decrement and its calculated spread. The correlation method is used to calculate the decrement from the magnitude of the decay rate of the interrelationship function, an approximate calculation scheme is shown in fig. 4.

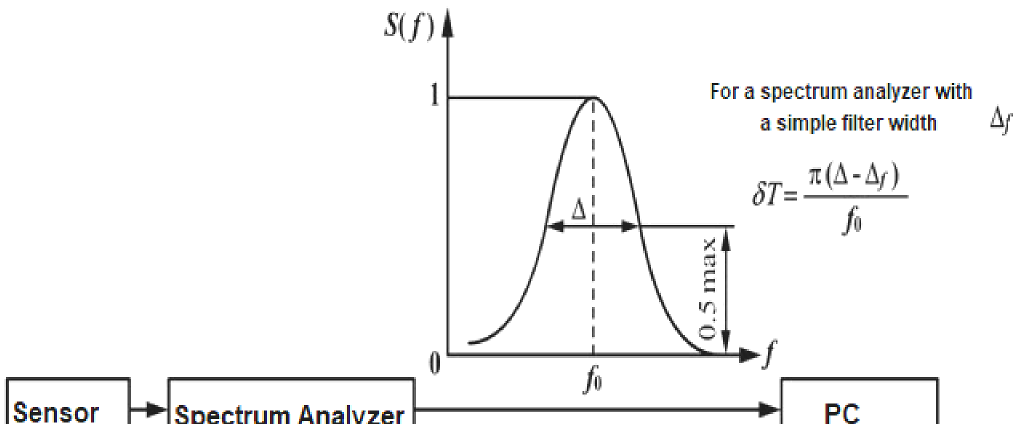

Fig. 3. The scheme for determining the decrement of oscillations by the spectral method

Рис. 3. Схема определения декремента колебаний по спектральному методу

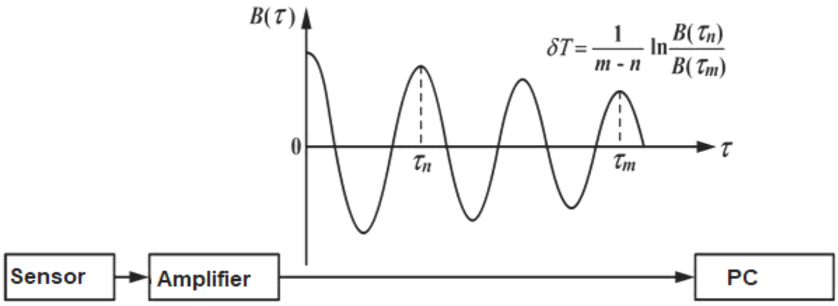

Fig. 4. The scheme for determining the decrement of oscillations from the magnitude of the decay rate of the interrelationship function

Рис. 4. Схема определения декремента колебаний по величине скорости затухания взаимокорреляционной функции

The EDD (external disturbing device) and EID (external impulse device) must provide the following [12]:

a) the correspondence of the disturbing amplitude of the most frequently observed natural pressure pulses in combustion chambers or gas generators;

b) the spectral composition of the pulse must have such a distribution of energy over the frequencies that would ensure that excitation in the combustion chamber (as an acoustic resonator) of pressure fluctuations of sufficient intensity in the required frequency region;

c) the possibility of changing the amplitude in the desired range and the stability of the characteristics during a repeated disturbance, as well as providing a series of periodic pulses;

d) ensure the introduction of disturbances for a wide range of operating pressures in the chamber or gas generator, as well as in the operation of the gas generator with an oxidizing environment.

At the same time, there are some operating restrictions imposed on EID, for example: the minimum possible diameter of the input port for introducing disturbances in order to reduce the effect on the integrity of the combustion chamber, as well as the minimum dimensions and resistance to high temperatures, vibrations, etc.

The most important is the choice of the place of the disturbance input. The answer to this question can be found from the prediction of the mode and the frequency of the natural oscillations of the path. An important fact is the method of optimal processing of experimental data, which provides sufficient accuracy and reliability of the obtained values of the damping decrement. The criterion for the adequacy of the stability margin for “hard” excitation [1–3; 5–14] is provided if the pressure oscillations after the pulse rapidly decay and a certain ratio is established between the initial peak deviation of the pressure from the mean and total high-frequency signal to the perturbation input. It is stated [3; 12] that in order to evaluate the stability of the working process to finite disturbances, it is required:

– introduce a pressure pulse in the range $15A_{sv} < A_m < 25A_{sv}$;

– determine the relaxation time of the process t_r, here A_m is the average value of the absolute maximum of the pulse;

– A_{sv} is the average rectified value of natural noises pulsations;

– $t_r = t_{1B} + t_b$ is the total relaxation time of the working process;

– t_{1B} is the time of action on the working process of the first disturbance wave;

– t_b is the time of decrease in the amplitude of pressure oscillations by ***e*** times.

The combustion chamber is supposed to be stable to finite disturbances [3; 10; 12], if the relaxation time is t_r < 15 ms.

Further, it should be noted that in testing of full-scale motors, it is necessary to evaluate the decrements and the spectra of pressure oscillations, both before the introduction of disturbance and after damping of the oscillations. Decrements of pressure fluctuations and spectra should not differ within the limits of measurement accuracy. A significant difference will mean the instability of the working process.

Conclusion. The algorithm is proposed for estimating reserves of stability towards the high high-frequency pressure oscillations in gas-generators and combustion chambers of liquid rocket engines, which means spectral processing of the combustion process reaction to pulsed artificial disturbances. In contrast to pyro cartridges, which are now used to create pulses with different gas pressure amplitudes in combustion chambers, electric pulse disturbing devices have been developed. They reduce the risk of damage to the components of LRE units in full-scale and model tests, and have an obvious prospect for widespread use.

References

1. Dvigateli raketnye zhidkostnye. *Metodika ocenki vysokochastotnoj ustojchivosti rabochego processa. OST V92-9000–78* [Liquid propellant engines. Method for assessing the high-frequency stability of the working process, Industry Standart V92-9000–78], NIIXimmash, 1978, 105 p.

2. Liquid propellant rocket combustion instability. Editor David T. Harrje, associate Editor Frederick H. Reardon. National aeronautics and space administration, Washington, 1972, 637 p.

3. Shibanov A. A., Pikalov V. P., Sajdov S. S., Pod red. d-ra tehn. nauk K. P. Denisova. M. *Metody fizicheskogo modelirovaniya vysokochastotnoy neustoychivosti rabochego processa v zhidkostnyh raketnyh*

dvigatelyah [Methods of physical modeling of high-frequency instability of the working process in liquid-fuel rocket engines], Moscow, Mashinostroenie, Mashino stroenie – Polet Publ., 2013, 512 p.

4. Narizhnyj A. A., Pikalov V. P., Carapkin R. A., *Generator impul'sov davleniya v akusticheskih polostyah kamer sgoranija i generatorov zhidkostnyh raketnyh dvigateley* [A generator of pressure pulses in the acoustic cavities of combustion chambers and generators of liquid rocket engines], Patent RF № 2523921, 31.05.2013.

5. Lebedinskij E. V., Kalmykov G. P., Mosolovet S. V. et al. *Rabochie processy v zhidkostnom raketnom dvigatele i ih modelirovanie* [Work processes in a liquid rocket engine and their modeling], Moscow, Mashinostroenie Publ., 2008, 511 p.

6. Lebedinskij E. V., Lozino-Lozinskaja I. G., Merkulov I. V. et al. *Akusticheskie sredstva bor'by s neustoychivost'yu gorenija* [Acoustic means to combat the instability of combustion]. Moscow, Centr Keldysha Publ., 2004, 205 p.

7. Mosolov S. V., Birjukov V. I. [Anti-pulsation partitions as a means of suppressing acoustic oscillations in the chambers of liquid rocket engines]. *Vestnik mashinostroeniya.* 2011, no. 11, P. 6 –11 (In Russ.).

8 Mosolov S. V., Birjukov V. I. [Hydrodynamic methods for ensuring the stability of the working process in combustion chambers of liquid rocket engines]. *Vestnik mashinostroeniya.* 2011, no. 12, P. 12–17 (In Russ.).

9. Birjukov V. I., Belaja A. Ju. [Ensuring the stability of the working process in the combustion chamber of liquid rocket engines]. *Vestnik Moskovskogo aviacionnogo instituta.* 2011, Vol. 18, no. 3, P. 110–115 (In Russ.).

10. Birjukov V. I., Mosolov S. V. Dinamika *gazovyh traktov zhidkostnyh raketnyh dvigateley* [Dynamics of gas paths of liquid rocket engines]. MAI Publ., 2016. 168 p.

11. Mosolov S. V., Biryukov V. I. Maintenance of Operational Stability in Liquid-Propellant Rocket Engines by Adjusting the Acoustic Properties of the Combustion Chambers. *Russian Engineering Research.* 2013, Vol. 33, no. 6, P. 313–318.

12. Dranovsky M. Combustion Instabilities in Liquid Rocket Engines: Testing and Development Practices in Russia, Progress in Astronautics and Aeronautics, AIAA, Reston, Virginia, 2007. 221 p.

13. Liquid Rocket Engine Combustion Stabilization Devices. USA, Nasa Space Vehicle Design Criteria (Chemical Propulsion), 1974. SP 8113. 127 p.

14. Yang V., Anderson W. Liquid Rocket Engine Combustion Instability, Progress in Astronautics and Aeronautics, AIAA, Washington, D. C., 1995. p. 169.

15. Skuchik E. *Osnovy akustiki.* [Fundamentals of Acoustics]. Moscow, Mir Publ., 1976, 542 p.

16. Barabanov S. A., Birjukov V. I. [Attenuation of forced oscillations and hydrostatic waves in the turbulent flow of extended tracts of power systems for liquid rocket engines] *Vestnik SibGAU.* 2015, Vol. 16, no. 2, P. 386–394 (In Russ.).

Библиографические ссылки

1. Двигатели ракетные жидкостные. Методика оценки высокочастотной устойчивости рабочего процесса: ОСТ В92-9000–78 / НИИхиммаш, 1978. 105 с.

2. Liquid propellant rocket combustion instability / Ed. David T. Harrje, associate Ed. Frederick H. Reardon ; National aeronautics and space administration. Washington, 1972. 637p.

3. Шибанов А. А., Пикалов В. П., Сайдов С. С. Методы физического моделирования высокочастотной неустойчивости рабочего процесса в жидкостных ракетных двигателях / под ред. д-ра техн. наук К. П. Денисова. М. : Машиностроение. Машиностроение – Полет, 2013. 512 с.

4. Пат. № 2523921 Российская Федерация от 31.05.2013 г. Генератор импульсов давления в акустических полостях камер сгорания и генераторов жидкостных ракетных двигателей / Нарижный А. А., Пикалов В. П., Царапкин Р. А. Опубл. 27.07.2014, Бюл. № 21.

5. Рабочие процессы в жидкостном ракетном двигателе и их моделирование / Е. В. Лебединский [и др.]; под ред. А. С. Коротеева. М. : Машиностроение, 2008. 512 с.

6. Акустические средства борьбы с неустойчивостью горения / Е. В. Лебединский [и др.]. М. : Изд-во ФГУП «Центр Келдыша», 2004. 205 с.

7. Мосолов С. В., Бирюков В. И. Антипульсационные перегородки как средство подавления акустических колебаний в камерах жидкостных ракетных двигателей // Вестник машиностроения. 2011. № 11. С. 6–11.

8. Мосолов С. В., Бирюков В. И. Гидродинамические способы обеспечения устойчивости рабочего процесса в камерах сгорания жидкостных ракетных двигателей // Вестник машиностроения. 2011. № 12. С. 12–17.

9. Бирюков В. И., Белая А. Ю. Обеспечение устойчивости рабочего процесса в камере сгорания жидкостных ракетных двигателей // Вестник Московского авиационного института. 2011. Т. 18, № 3. С. 110–115.

10. Бирюков В. И., Мосолов С. В. Динамика газовых трактов жидкостных ракетных двигателей. М. : Изд-во МАИ, 2016. 168 с.

11. Mosolov S. V., Biryukov V. I. Maintenance of Operational Stability in Liquid-Propellant Rocket Engines by Adjusting the Acoustic Properties of the Combustion Chambers // Russian Engineering Research. 2013. Т. 33, № 6. С. 313–318.

12. Dranovsky M. Combustion Instabilities in Liquid Rocket Engines: Testing and Development Practices in Russia, Progress in Astronautics and Aeronautics, AIAA. Reston, Virginia, 2007. 221 p.

13. Liquid Rocket Engine Combustion Stabilization Devices / Nasa Space Vehicle Design Criteria (Chemical Propulsion). USA, 1974. SP 8113. 127 p.

14. Yang V., Anderson W. Liquid Rocket Engine Combustion Instability, Progress in Astronautics and Aeronautics, AIAA. Washington, D. C., 1995. P. 169.

15. Скучик Е. Основы акустики. М. : Мир, 1976. Т. 2. 542 с.

16. Барабанов С. А., Бирюков В. И. Затухание вынужденных колебаний и гидроударных волн в турбулентном потоке протяженных трактов систем питания жидкостных ракетных двигателей // Вестник СибГАУ. 2015. Т. 16, № 2. С. 386–394.