METHODS OF FUNCTIONAL DIAGNOSTIC OF LPRE ON THE BASIS OF MATHEMATICAL MODELS

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Introduction

To ensure reliability of liquid propellant rocket engines (LPRE), used in modern space-rocket systems, and to decrease the specific cost of a payload injected into space – it is one of major problems at development of modern space-rocket systems and systems of reusable operation specially.

If to take into account, that the LPRE costs constitute 20…40% of the rocket total development cost, decreasing of the LPRE development costs and decreasing of operation cost are highly actual problems. The main way of savings - reduction of quantity of engines intended to development of design and improvement of design up to required reliability level. Thus each engine should enable to reusable tests, i.e. have sufficient safe life. The decision about each consequent test is received after analysis of the engine condition after previous test on the basis of the information received as a result of functional diagnostic and checks by methods of non-destructive monitoring.

In this connection the receiving a reliable estimation of technical condition of LPRE at all phases of production and operation: at stand tests, preflight and interflight service takes the great importance. All this stimulates improvement of existing methods and instruments of LPRE diagnostic as well as development of new methods and instruments of LPRE diagnostic.

NPO Energomash has more than 25-year's experience of diagnosing of condition of LOX-kerosene LPRE of large thrust - RD170, RD171, RD120 and RD180, which had conducted hot tests at development, acceptance-check and operation.

A problem (at high power efficiency of LPRE) of a fivefold margin on safe life and quantity of restarts over flight safe life was posed in NPO Energomash for the first time at development of powerful LOX-kerosene LPRE for “Zenit”, “Energia” launch-vehicles and “Energia”-“Buran” space-rocket system of a new generation. It meant, that, taking into account a two acceptance-check tests (main and reserve), each engine should have a sevenfold margin on the indicated parameters. The last requirement meant operation time increase over the flight minimum in 7 times, increase of quantity of transient modes (start-up and shut-down) effects also in 7 times without taking into account a guarantee margin. Earlier, for engines of expendable operation, these margins averaged not more than 2…2,5 flight safe lifes. Thus, in case of reusable flight operation, the required guaranteed operating time of each engine has increased on the order in comparison with expendable LPRE. It was necessary for a RD170 engine, intended for a first stage of “Energia” and “Energy”-“Buran”, to ensure 10-time flight operation in addition to the guaranteed margin on safe life and number of start-ups.

The problem has become complicated in a middle 1990, when the development of engines for American “Atlas” LV and Russian “Angara” LV began. Hereinafter commercial situation in the market has dictated more strict constraints: it was required to reduce quantity of engines intended for the experimental purposes up to 10 specimens. If the engine of “Energia” launch-vehicle was developed up to a required level of reliability after 170 tests of 60 engines, 100 tests of only 10 engines were conducted for “Atlas” launch-vehicle engine development. Stand development of LOX-kerosene RD170 LPRE for reusable operation was completed practically. The flight operation was not realized because of termination of “Energia”- “Buran” program.

Under the perspective plans of the Russian Khrunitchev’ company the development of the reusable space launch-vehicle “Baikal” is supposed. The reusable LOX-kerosene RD191 LPRE will be used on a first stage of this system. Therefore the decisions ensuring reusable operation of engine are incorporated already today in the scheme, design and system of engine acceptance and its operation.

The stand monitoring instruments and technical diagnostic systems (TDS) are used now at single tests, and also at repeated tests without engines removal off-the-stand. The basic problem decided by such TDS consists in validation of engines operation precision at acceptance tests.

The same principles, which used for diagnosing of expendable engines, can be assumed as the basis of TDS of reusable LPRE:

- hierarchical system of engine diagnosing, which provides sequential transition to consequent levels of diagnosing in case of need of fault detailings;
- automation of all procedures at a data preparing level, primary processing and at a final phase at decision making;
- adaptation to a particular condition of measurement system and to engine performances;
- principles of forming of the diagnostic signs, which ensure univocal physical interpretation of received results and have local sensitivity to faults;
- examination of a hardware condition by methods of non-destructive monitoring;
- decision making on all complex of systems, which include in TDS.

At development of reusable TDS it is necessary also to take into account features of returning of the engine on the Earth and strict requirements on limitation of diagnosing time within interflight period. The special responsibility thus to put on decision making about next flight use of engine.

It is offered to use for troubleshooting:

- the formalized methods which provide flexible computer algorithms of their realization;
- heuristic methods based on experience of the experts and which provide dialog mode with computer instruments of diagnostic.

The methods based on use of next models are the formalized methods:

- mathematical models (MM) which describe working processes in engine at stationary and transient modes in low-frequency area;
- statistical models.

The use of mathematical modelling for analysis of engines condition increases reliability of decision making by results of test and reliability of the forecast of positive outcome of each consequent test of LPRE. It is connected that MM ensures correct (from the point of view of modern knowledge of the physical nature of working processes) description of correlations of their parameters. In MM the degree of a details of the physical processes description is determined with the help of equations (connections), the factors of which correspond parameters of design elements: hydroresistances, pressure head, power performance of pumps etc. Besides the capability to evaluate a sensitivity of a measured parameters of processes to faults is a distinctive feature of MM. It has effected, for example, on a modification of factors of MM. Structure of MM as system of equations generates numerous algorithms of identification, for the substantiation of which mathematical analysis instrument can be used. These features in a combination with the nomenclature and accuracy of measured parameters ensure a capability to receive not only qualitative, but, that is more important for reusable LPRE, quantitative estimations of a modification of parameters of design elements within engine operation.

Problem of functional diagnosing is brought methodologicalally to search of such fault, which causes a violation (modification) of initial correlations between parameters of working processes. The correlations between these parameters are described by the known physical laws at a modern level of science with equations set. These parameters, even partially, should be accessible for measurement and react to violation of correlations. The analysis of misalignments between measured and design values of parameters of working processes with the help of special algorithms ensures localization of fault within design element, the operation of which is described by one or several equations, and determines a degree of a modification of parameters of this element.

The complication of detection of a place (localization) of fault and definition of degree of modification of design parameters is caused basically by following reasons:

- the disturbance, caused by fault, is distributed in continious medium fast enough (for example, for LPRE the hold time can constitute not more than $10^{-2}...10^{-3}$ s), and is fixed in a point enough removed from a place of it (fault) origin;
- a restricted (by formalism of the mathematical description of working processes) sensitivity of measured parameters to modification of parameters of design elements results to decreasing of quantity of locally troubleshot loops;
- the inaccuracies of measurements result to forced expansion of the tolerances on inspected parameters.

Now at NPO Energomash at analysis of fire tests of LPRE the systems of functional diagnostics (SFD), based on MM of working processes in low-frequency area, i.e. in 0... 100 Hz range, are used. These models describe a stationary and transient processes with lumped parameters. Such models are most acceptable, as the nominal system of measurement registers mainly a local parameters of working processes (pressures, temperatures, consumptions of propellants etc.). The models of coordination of measured pulsation parameters of propellants or vibration of design elements with computational ones with mathematical models are used now basically for qualitative estimations.

The methods of functional diagnostic are considered in the present paper. Such methods is considered as a main part of a system of technical diagnostics of LPRE.

1. Main concepts, limitation, estimations

It is known, that in the general case the problem of trouble shooting can not be decided without introduction of some natural limitations, within framework of which it becomes solvable. For example, it is necessary, that the fault arises in any one and only one design element and causes a connection breakdown between parameters defined in model of operationable object etc. We shall enter an important for understanding following limitations, definitions and estimations.

1.1. Fault

Let's consider at first for a simplicity an ideal case, when there are not any errors of measurement, modelling etc. We shall suspect also, that all parameters and disturbances, introduced in MM, are accessible for measurement. Let's designate these measured parameters and disturbances as $\vec{x}^*$ and $\vec{x}_d^*$ accordingly. Then, if the connections between parameters of MM are not disrupted, all equations f_k after substitution in them of all measured values turn to identities:

$$f_k\ (\vec{x}^*, \vec{x}_d^*) \equiv 0,\quad k = 1, 2, \ldots, n,$$

where k - number of an equation, n – quantity of equations. Let's suspect, that the fault of a design element disrupts connection between parameters described by an equation f_k. Such fault can be detected within the framework of a considered methodology only then, when there is a misalignment of left-hand and right-hand part of an equation:

$$f_k\ (\vec{x}^*, \vec{x}_d^*) = \delta f_k \neq 0$$

Therefore, δf_k is possible formally to consider as the diagnostic sign (DS) of absence (if δf_k = 0) or availability (if $\delta f_k \neq 0$) of connection breakdown between parameters described by an equation f_k.

Advantage of such method of the description of fault is absence of the necessity to determine a kind of new connection originating at fault between parameters. However from here follows that to define formally, the misalignment δf_k is caused by a development of fault or modification of external (in relation to engine) any disturbance, without measurement of such disturbance it is impossible. In essence, here there is a same uncertainty which is stated in Kirchhoff theorem for an acoustic field [1]. Therefore formalized decision of a search problem of a perturbation source - internal or external one in relation to object of monitoring - is possible only within the framework of the applicable limitations.

1.2. Diagnostic signs

The diagnostic sign δf_k can be represented on misalignments δx_j of computational x_j^0 with MM and measured at test x^* values of variables x_j:

$$\delta x_j = x_j^* - x_j^0, \qquad j = 1, 2, \ldots, p$$

or in a dimensionless view

$$\delta \bar{x}_j = \frac{x_j^* - x_j^0}{x_j^*}, \quad x_j^* \neq 0$$

where j - number of measured parameter, p - quantity of measured parameters, and to consider δx_j as DS, the physical sense of which does not cause doubt. With the help this DS, using special algorithms, there are possible to define the fault within one or several connections called as loop.

1.3. Sensitivity

Let's enter natural in the given problem definition of sensitivity of measured parameter x_j to violation δf_k of connection f_k:

$$r_{jk} = \frac{\delta x_j}{\delta f_k}$$

where r_{jk} - factor of sensitivity indicating as measured parameter x_j^* is changed at misalignment of a right part of connection f_k at it violation as a result of fault. It is understandable, that this factor characterizes only properties of physical and mathematical "designs" incorporated in MM. A fairly following ratio:

$$r_{jk} = (-1)^{k+j} \frac{J_{kj}}{J},$$

where J - Jacobian of initial set of equations, J_{kj} - minor of Jacobi matrix obtained by deletion from it line *k* and a column *j*.

1.4. Extreme achievable accuracy

The misalignment δf_k is presented on an estimation δa_k of modifications of MM factors - parameters of design elements with the help of a ratio:

$$\delta f_k = -\sum_{m=1}^{m=q} \left[\frac{\partial f_k}{\partial a_{km}} \sigma(\delta a_{km}) \right]^2 = -\delta A_k$$

The statistical estimations δa_k can be received, taking into account measurement errors, i.e. mean value:

$$M_j(\delta A_k) = M\left(\frac{\delta x_j}{r_{jk}}\right) = \frac{1}{r_{jk}} \sigma(\delta x_j),$$

$$r_{jk} \neq 0$$

and mean square deviation:

$$\sigma(\delta A_k) = \sigma\left(\frac{\delta x_j}{r_{jk}}\right) = \frac{1}{r_{jk}} \sigma(\delta x_j)$$

This ratio establishes correlation between errors of measurements, sensitivity of MM, values of the diagnostic signs and extreme achievable accuracy (resolution capability) of definition of parameters of design elements.

2. Methods of diagnosing

2.1. Method of structural elimination

Idea of diagnosing by a method of structural elimination can be presented schematically as follows. Let's suspect, that the fault has resulted to modification of connection between parameters described by an equation or a loop f_k in initial model (set of equations) A. If to exclude this "disrupted" equation or loop from A (in a fig. 1 «Oxidizer pump»), remained, the truncated part of equations set A_k will still describe connection in normally operating, "operationable" part of engine. To decide a set of equations A_k, it is necessary to close by trivial equations $x_j = x_j^*$. Measured parameter x_{jk}^* we shall term as eliminating parameter for an equation f_k. If the loop (some equations) is excluded, quantity of eliminating parameter should be equal to quantity of eliminated equations.

Having decided system A_k, we shall find a design value x_{qk}^0 of any other measured parameter x_q^*, which we shall term as monitoring parameter. The misalignment $\delta x_{qk} = x_{qk}^0 - x_q^*$ is DS of connection f_k condition. Sequentially excluding "suspected" connections in A_k, it is possible to locate fault. Namely, such connection f_p is assumed as disrupted one, at elimination of which a condition $\delta x_{qk} = 0$ will be realized. If there are a some such connections, they will derivate a locally troubleshot loop, within of which it is formally impossible to define, which connection is disrupted.

For correct realization of a procedure of elimination the mathematical apparatus is developed which is presented in [2]. Easy to note, that the localization of fault in a method of structural elimination is possible only at measurement as the minimum of two parameters (except for, certainly, measurements of the external factors, which we shall term as closing parameters). The increase of quantity of equations and (or) measured parameters results to increase of depth of diagnosing, and also enables to reject inadequate measurements. Thus the system of measurement, as shown, should be consists of three subsets: closing, eliminating and monitoring measurements, which are selected from most reliable ones.

2.2. Method of frequency factors

The method of structural elimination without any modifications can be distributed on diagnosing in frequency area. However here procedure of diagnosing can be essentially simplified. Let's represent a linearized set of equations of MM in a time domain with the help of a Laplace transformation in frequency area. This transformation is designated by sign "~". Let's suspect, that the fault has resulted to a connection breakdown between parameters described by an equation $\tilde{f}_k$. Let $\tilde{x}^0$ and $\tilde{x}^k$ - solution of a linear system of equations in frequency area before and after origin of fault accordingly, and $\tilde{x}^0$ - solution of a set of equations, in which the right parts of all equations, except for f_k, are equal to zero. Let's designate $\tilde{\delta}_k = \tilde{x}^k - \tilde{x}^0$, then for parameters with indexes j and q according to a Cramer's rule the next ratio is fair:

$$K_{jq}^k = \frac{\tilde{\delta}_j^k}{\tilde{\delta}_q^k} = \frac{\tilde{x}_j^o}{\tilde{x}_q^0} = (-1)^{j-q}\frac{\Delta_{kj}}{\Delta_{kq}},$$

where Δ_{kj} and Δ_{kq} - determinants received by deletion of line k and column j and q accordingly in a matrix of a set of equations in frequency area. Naturally, we shall suppose, that $\Delta_{kj} \neq 0$ and $\Delta_{kq} \neq 0$ in analyzable frequency band. As we see, the given ratio is a constant describing structure of a initial set of equations, i.e. it is not changed at disturbances which acting on object of monitoring at normal operation, at a disturbance caused by fault of connection $\tilde{f}_k$. Factor K_{jq}^k is called as a computational complex factor of connection of parameters $x_j(t)$ and $x_q(t)$ at a disturbance of connection $\tilde{f}_k$.

Let's remark, and it is important, that the connection factors K_{jq}^k can be calculated prior to the beginning experiment. The diagnostic signs - amplitude-frequency characteristics of deviations - are formed on the basis of obtained ratio:

$$\delta_{jq}^k = \left|K_{jq}^k - K_{jq}^*\right|$$

where $K_{jk}^* = \frac{\tilde{\delta}_j^*}{\tilde{\delta}_k^*}$ - value of a connection factor obtained on measured at experiment deviations of parameters. It is analytically proved, that in an ideal case without dissipation (friction etc.) in a dynamic system it is impossible to locate the fault on some particular frequencies, including natural ones. It is understandable, that in actual physical systems because of processes of dissipation (friction etc.) the amplitude-frequency characteristic δ_{jq}^k differs from zero on all frequencies of operationable object, including natural ones, however it can contain the local minimums on natural frequencies. For example, if the connection factor – ratio of a Fourier transform of the turbine rotation to a Fourier transform of fuel pressure before injectors of the chamber - is used for DS forming, the typical behavior of amplitude of such DS at violation of oxidizer pump head on different frequencies is shown in a fig. 2. Therefore about of some frequencies the diagnostic signs are least responsive to fault, that it is necessary to take into account at selection of ranges of troubleshot frequencies.

The procedure of monitoring is divided into following phases.

1. The misalignments of a kind δ_{jk}^k on consecutive intervals of times ΔT_i and ΔT_{i+1} in given frequency range Ω are calculated.

2. If condition is satisfied:

$$\delta_{jk}^k(\omega_i) = 0, \qquad k=1, 2, \ldots, n$$

for all $\omega_i \in \Omega$, a decision on absence of fault is made.

3. If the condition in p.2 is executed not for all k, but only for any k = $k_1, k_2, \ldots, k_n$, p ‹ n, i.e. for all remaining k = $k_1, k_2, \ldots, k_n$ the condition is satisfied: $\delta_{jq}^k(\omega_i) \neq 0$ for all

dition is satisfied: $\delta_{jq}^{k}(\omega_i) \neq 0$ for all $\omega_i \in \Omega$, a decision on availability of violation (fault) of any one of connections $k_1, k_2, \ldots, k_p$ is made.

3. Tolerances on the diagnostic signs

The known estimations of SFD quality are basically integral one and are determined by probabilities of a false estimation, miss of defect and concerned with them probabilities of the correct decision. However for the particular decision making about engine condition, specially at its reusable operations, it is necessary to know particular numeric estimations of parameters of design elements. The obtaining of such kind of estimations is hampered by that the parameters of design and processes are presented on DS on a complex chain «MM - measurement system - algorithms of diagnosing», errors analysis in each link of which is enough complex problem. Definition of acceptable values of DS, corresponding with normal operation of a particular engine can divide on following phases:

1. Definition of acceptable values of DS, corresponding with an extreme achievable accuracy of dispersion of parameters of design and processes, see section 1.

For example, it is possible to evaluate the tolerances on measured parameters x_j^*, which define normal operation, knowing technological dispersion of parameters of design $\sigma(\delta a_{km})$, described by connection f_k :

$$\sigma(\delta x_{jk}) = r_{jk}\sqrt{\sum_m \left[\frac{\partial f_k}{\partial a_{km}}\sigma(\delta a_{km})\right]^2}$$

2. Assignment of the tolerances on DS on probability of hit in a given interval 3. Correction of MM and tolerances on DS after realization of acceptance-check tests.

4. Correction of MM after each flight for reusable engine with accounting of modifications of design elements parameters as result, for example, wearing.

For an estimation of acceptable values of DS, specially at the SFD development phase, it is possible to apply statistical modelling of errors of autonomous tests of engine units, errors of measurements, errors of production on the basis of methods such as Monte-Carlo.

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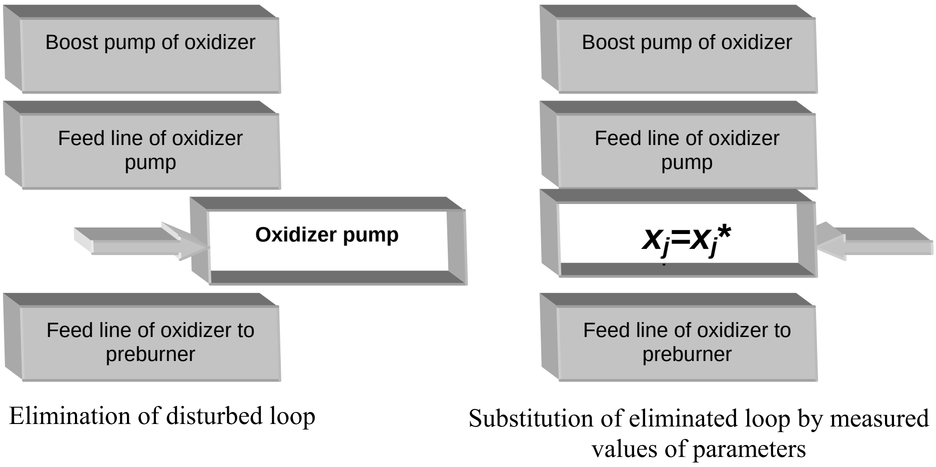

Fig. 1. Scheme of idea of method of structural elimination

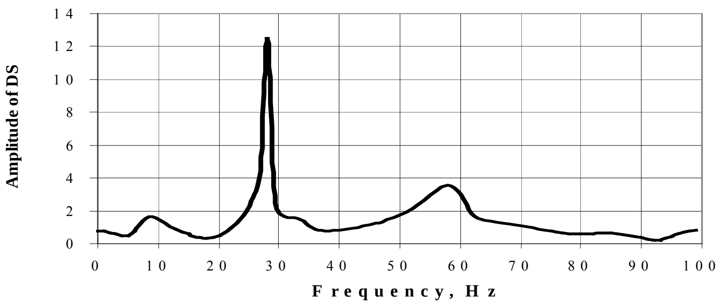

Fig. 2. Relation of amplitude of DS against frequency at violation of oxidizer pump head