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DEVELOPING AN ALGORITHM FOR MONITORING GAS GENERATORS OF HYDROGEN STORAGE AND SUPPLY SYSTEMS

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Abstract

In relation to the main element of the hydrogen storage and supply system based on the hydro-reacting composition – the gas generator – an algorithm for its control has been developed. The development of such an algorithm is carried out in three stages. At the first stage, the problem of formalizing the hydrogen generation process is solved. Formalization of this process is carried out using the transfer function of the gas generator. The use of the criterion for the minimum error of the mismatch of the given amplitude-frequency characteristics of the gas generator allows to represent its transfer function in the form of a transfer function of the inertial link. At the second stage, the problem of determining the conditions for the occurrence of self-oscillations in the pressure stabilization subsystem is solved. A prerequisite for the emergence of a self-oscillating mode of operation of the hydrogen storage and supply system is the presence of a relay static characteristic of the pressure sensor. For the characteristic parameters of such a system, the ranges of values of the parameters of self-oscillations, frequencies and amplitudes, are determined. For these parameters, analytical expressions are obtained, which include the main parameters of the pressure stabilization subsystem in the hydrogen storage and supply system.

At the third stage, the problem of forming a gas generator control algorithm is solved. As a test action in the implementation of the control algorithm, self-oscillations in the pressure stabilization subsystem are used. The control algorithm for the gas generator of the hydrogen storage and supply system includes determining the parameters of self-oscillations and comparing their values with the values obtained a priori.

A typical diagram of a hydrogen storage and supply system is presented, in which the developed gas generator control algorithm is implemented.

Keywords: hydrogen storage and supply system, gas generator, self-oscillating mode of operation, self-oscillation parameters, control algorithm.

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1. Introduction

One of the promising directions for improving energy systems is the use of hydrogen as a working fluid. Of particular relevance is the use of hydrogen in the energy systems of mobile objects that operate offline. One of the advantages of hydrogen energy systems is the complete absence of carbon emissions [1]. Such systems include systems for storing and supplying hydrogen in a chemically bound state, in particular, based on hydroreacting compositions. The storage of hydrogen in solid compounds seems to be the most significant technical solution, since it is a safer and more convenient method compared to high-pressure compression and liquefaction technologies [2]. The main element of hydrogen storage and supply systems of this type is a gas generator. The safe operation of hydrogen storage and supply systems necessitates the provision of such values of their parameters and characteristics that guarantee compliance with the requirements of regulatory documents [3]. In this regard, an urgent task is to ensure compliance between the technical characteristics of the main element of the hydrogen storage and supply system and the requirements of regulatory documentation. One of the stages of solving such a problem is the development of appropriate algorithms for monitoring the technical condition of gas generators of hydrogen storage and supply systems, which to a greater extent take into account the features of their construction.

The biggest problem in the use of hydrogen fuel is the creation of hydrogen storage and supply systems, especially for airborne applications [2]. Modern technologies used for hydrogen storage include compression under a pressure of about 70 MPa, liquefaction at cryogenic temperatures (about 20 K), and adsorption in solid phase compounds. The last option is preferred. Recently, there has been a trend in the use of hybrid energy systems (HES) [4]. One of such options for building a hybrid storage system is given in [5], which also presents the results of its tests. It is noted that when using a fuel cell with metal hydride, there is a more uniform distribution of energy compared to the battery mode. The disadvantages of fuel cells in [6] include a short service life and low reliability. When hydrogen is produced, a large amount of heat can be released – up to 15.0 $MJ\cdot kg^{-1}$ [7]. This mode of hydrogen generation does not exclude the occurrence of a fire and explosion hazard situation [8], as a result of which there is a need to assess the potential hazards of the hydrogen storage system. To obtain estimates of the potential hazards of hydrogen storage systems, information about the temperature [9] or the pressure of the generation process [10] is used. The authors of [11] propose a method for evaluating the efficiency of a hydrogen generator, taking into account the requirements for auxiliary subsystems. However, the information obtained in this way is not used to assess its technical condition. In industrial samples of hydrogen generators, as a rule, one or two parameters of the generation process are controlled [12]. In the overwhelming majority, such parameters are controlled that characterize the local properties of hydrogen generators. In [13], in relation to liquid hydrogen (LH2) storage systems, which is the main component of hydrogen refueling stations (HRS), an approach to assessing the risk of unintentional LH2 emissions is considered. The following failure scenarios for the hydrogen storage system are considered: failure of the safety valve system in the liquid storage tank, failure of the pneumatically actuated valve and rupture of the evaporator. Methods for detecting failures are discussed. Among the new technologies for monitoring the technical condition of an object, the «digital twin» technology should be attributed [14]. This technology provides for the creation of hardware and software components of the object of study. The authors use this approach to manage the risks of failures in relation to a hydrogen pressure vessel.

It should be noted that when using estimates associated with the risks of failures, there are difficulties that are due to the need to use statistical data. In most cases, especially when using new technologies, such data are not available.

The work [10] considers an algorithm for monitoring the technical condition of the gas generator of the hydrogen storage and supply system using its amplitude-frequency characteristic. The paper [15] proposes control algorithms for such a gas generator using its phase-frequency characteristic. When implementing such algorithms, the dynamic properties of the gas generator are taken into account, and its frequency characteristics are determined promptly and without the use of equipment that implements harmonic test signals [16]. It is possible to simultaneously use the amplitude-frequency and phase-frequency characteristics of the gas generator in the formation of its control algorithm [17]. This approach makes it possible to more fully take into account the dynamic properties of the gas generator.

It should be noted that when developing algorithms for monitoring the technical condition of gas generators of hydrogen storage and supply systems using their frequency characteristics, it is necessary to use an external test effect. With the help of such an external test effect, the frequency characteristics of the gas generator of the hydrogen storage and supply system are obtained.

Another approach is possible to take into account the dynamic properties of the gas generator when monitoring its technical condition. This approach involves the use of a self-oscillatory mode of operation of the gas generator [18], in which the parameters of self-oscillations are determined. A prerequisite for the self-oscillating mode of operation of the gas generator is the presence of a non-linear static characteristic of the sensor in the pressure stabilization circuit of the gas generator. In this regard, among the problems associated with ensuring the safe operation of hydrogen storage and supply systems is the problem of organizing the control of the technical condition of both the system as a whole and its main elements.

2. Materials and methods of research

2. 1. Methods

Conducting research includes the use of theoretical methods based on the application of the integral Laplace transform and functions of a complex variable. To assess the adequacy of the obtained mathematical models, a criterion was used that minimizes the absolute mismatch error between the a priori given model and the model under study. The study of the self-oscillating mode of operation of the system under study is based on the use of the harmonic balance equation. To obtain practical dependencies, standard software procedures were used, for example, the Maple package.

2. 2. Substantiation of the control algorithm for the gas generator of the hydrogen storage and supply system

The main tasks in creating a gas generator control algorithm include:

– obtaining a simplified mathematical description of the processes occurring in the gas generator using the criterion of the minimum absolute error of the mismatch of its amplitude-frequency characteristics;

– obtaining analytical expressions for the parameters that characterize the self-oscillatory mode of operation of the hydrogen storage and supply system;

– development of an algorithm for controlling the gas generator of the hydrogen storage and supply system, which is based on the use of information about the self-oscillatory mode of its operation.

2. 2. 1. Simplified mathematical description of the processes occurring in the gas generator

The system of storage and supply of hydrogen based on the hydroreacting composition in a generalized form has a block diagram shown in **Fig. 1**.

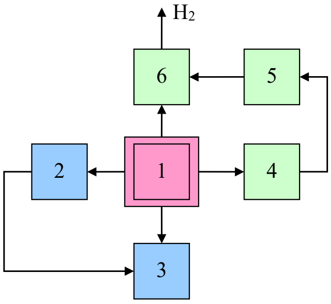

Fig. 1. Structural diagram of the hydrogen storage and supply system

The main element of such a system is the gas generator 1, the operation of which is provided by the water stabilization subsystem and the pressure stabilization subsystem. The first subsystem includes a measuring device 2 and an actuator 3. The second subsystem includes a pressure sensor 4, an amplifier 5 and a device for regulating the area of the outlet in the gas generator 1. The dynamic properties of the gas generator are determined by its transfer function, which has the form [10]:

$$W_1(p) = K_1(1-\tau_1 p)\left[(1+\tau_2 p)(1+\tau_3 p)\right]^{-1}, \tag{1}$$

where K_1 – transmission coefficient; τ_i – i-th time constant ($i = 1, 2, 3$); p – complex number.

In the first approximation, the transfer function (1) can be replaced by the expression:

$$W_{10}(p)=K_1(1+\tau_0 p)^{-1}, \tag{2}$$

where τ_0 – time constant to be determined.

To determine the parameter τ_0, let's use the criterion:

$$abs(\delta)=\min, \tag{3}$$

where $\delta=a_1(\omega)-a_{10}(\omega)$; ω – circular frequency; $a_1(\omega)$ and $a_{10}(\omega)$ – reduced amplitude-frequency characteristics of the gas generator, which are described by the expressions:

$$a_1(\omega)=\left[\left[1+(\omega\tau_1)^2\right]\left[\left[1+(\omega\tau_2)^2\right]\left[1+(\omega\tau_3)^2\right]\right]^{-1}\right]^{0.5}; \tag{4}$$

$$a_{10}(\omega)=\left[1+(\omega\tau_0)^2\right]^{-0.5}. \tag{5}$$

Fig. 2 shows dependences $abs(\delta)=f(\omega)$ for characteristic values of *i*-th time constants equal to $\tau_1=7.9$ ms; $\tau_2=6.5$ ms and $\tau_3=14.4$ ms [15].

For the case under consideration, the mismatch error at $\tau_0=(11.5\div13.5)$ ms does not exceed 5.0 %.

Fig. 3 shows the dependence of the mismatch error on the value of the time constant τ_0.

From the dependence shown in **Fig. 3**, it follows that at $\tau_0\sim12.8$ ms, the minimum mismatch error between the frequency characteristics $a_1(\omega)$ and $a_{10}(\omega)$ is achieved. This dependence was obtained on the basis of the data presented in **Fig. 2**.

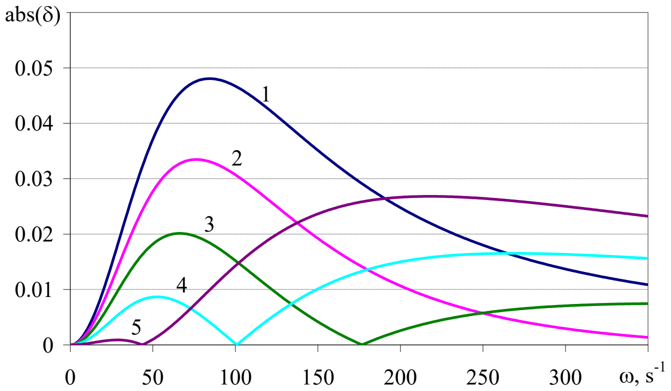

Fig. 2. Dependences of mismatch error on frequency: 1 – $\tau_0=11.5$ ms; 2 – $\tau_0=12.0$ ms; 3 – $\tau_0=12.5$ ms; 4 – $\tau_0=13.0$ ms; 5 – $\tau_0=13.5$ ms

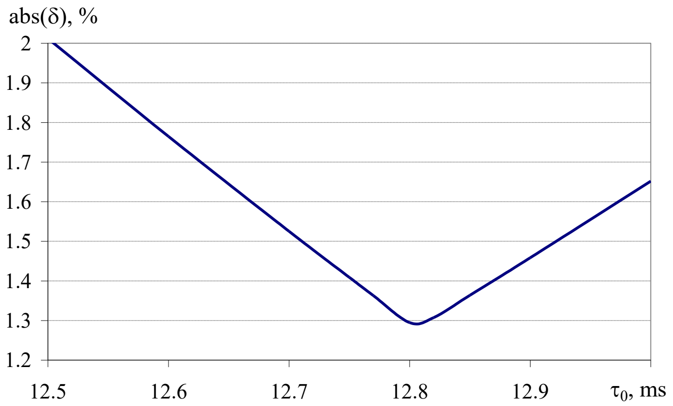

Fig. 3. Dependence of mismatch error on time constant τ_0

2. 2. 2. Parameters of self-oscillations

A feature of the operation of the hydrogen storage and supply system is that the pressure stabilization subsystem is non-linear. The non-linearity of the system is due to the relay characteristic of the pressure sensor 4 (**Fig. 1**), which has a dead zone with a width of 2σ. In such a subsystem, the regime of self-oscillations of frequency ω0 and amplitude A is possible under the condition:

$$J(A)W(j\omega) = -1, \tag{6}$$

where *J*(*A*) – equivalent complex transfer coefficient of a non-linear element – a pressure sensor; *W*(*j*ω) – amplitude-phase frequency characteristic of the linear part of the pressure stabilization subsystem; *j* – imaginary unit.

For the case under consideration:

$$J(A) = \frac{4}{\pi} N\sigma A^{-1}\left[1-\left(\sigma A^{-1}\right)^2\right]^{0.5}; \tag{7}$$

$$W(j\omega) = K\left[j\omega\left(1+j\omega\tau_0\right)\left(1+j\omega\tau\right)\right]^{-1}, \tag{8}$$

where $N = D\sigma^{-1}$; *D* – parameter of the relay characteristic of the pressure sensor; τ – time constant of the device for regulating the area of the outlet 6 of the gas generator 1 (**Fig. 1**); *K* – transfer coefficient of the linear part of the subsystem.

Equation (6) corresponds to a system of equations of the form:

$$J(A)\mathrm{Re}W(j\omega) = -1;\ J(A)\mathrm{Im}W(j\omega) = 0, \tag{9}$$

where

$$\mathrm{Re}W(j\omega) = -K\left(\tau_0+\tau\right)\left[\omega^2\left(\tau_0+\tau\right)^2+\left(1-\omega^2\tau_0\tau\right)^2\right]^{-1}; \tag{10}$$

$$\mathrm{Im}W(j\omega) = -K\left(1-\omega^2\tau_0\tau\right)\left[\omega^3\left(\tau_0+\tau\right)^2+\omega\left(1-\omega^2\tau_0\tau\right)^2\right]^{-1}. \tag{11}$$

From the second equation (9), taking into account (11), the expression for the frequency of self-oscillations ω_0 follows:

$$\omega_0 = \left(\tau_0\tau\right)^{-0.5}. \tag{12}$$

Fig. 4 shows the dependence $\omega_0 = \omega_0(\tau)$ at $\tau_0 = 12.75$ ms.

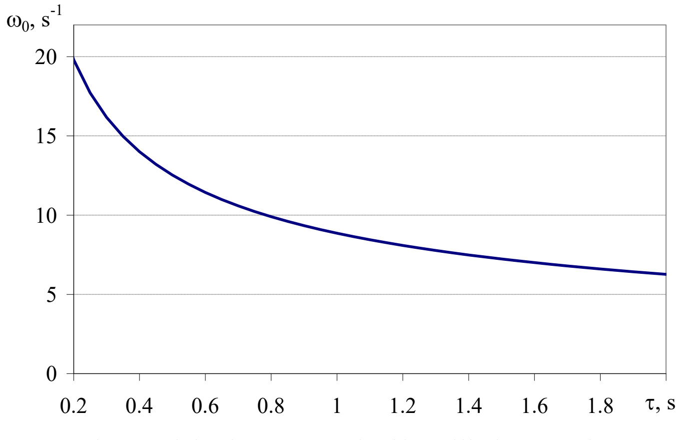

Fig. 4. Dependence of the frequency of self-oscillations on the parameter τ

After substituting (12) into the first equation of system (9), taking into account (10), let's obtain a biquadratic algebraic equation for the amplitude A of self-oscillations:

$$x^4 - x^2 + \left[0.25\pi\left(\tau_0 + \tau\right)\left(K\tau_0\tau N\right)^{-1}\right]^2 = 0, \tag{13}$$

where $x = \sigma A^{-1}$. It follows from the solution of this algebraic equation that the amplitude of self-oscillations is determined by the expression:

$$A = \sigma\left[0.5\left[1 \pm \left[1 - \left[0.25\pi\left(\tau_0 + \tau\right)\left(K\tau_0\tau N\right)^{-1}\right]^2\right]^{0.5}\right]\right]^{-0.5}. \tag{14}$$

Graphic dependence $A = A(\tau)$ at $\sigma = 50$ kPa; $D = 5.0$ V; $\tau_0 = 12.75$ ms is shown in **Fig. 5**. **Fig. 6** shows the dependence $A = A(K)$ for two values of the parameter τ. The upper part of the graphic dependence corresponds to the self-oscillatory mode of operation of the hydrogen storage and supply system.

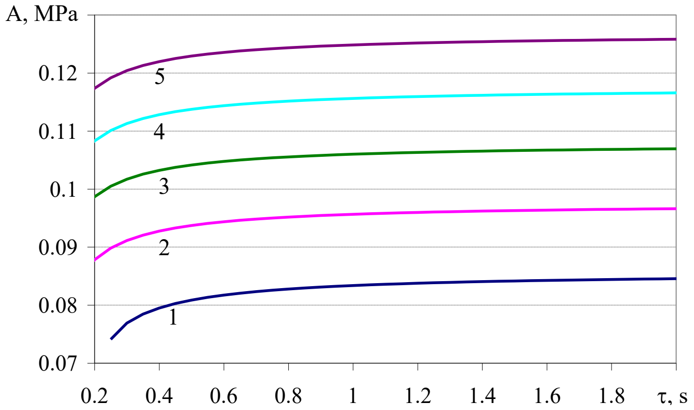

Fig. 5. Dependence of the amplitude of self-oscillations on the parameter τ: 1 – $K = 0.65$ MPa·V^{-1}; 2 – $K = 0.7$ MPa·V^{-1}; 3 – $K = 0.75$ MPa·V^{-1}; 4 – $K = 0.8$ MPa·V^{-1}; 5 – $K = 0.85$ MPa·V^{-1}

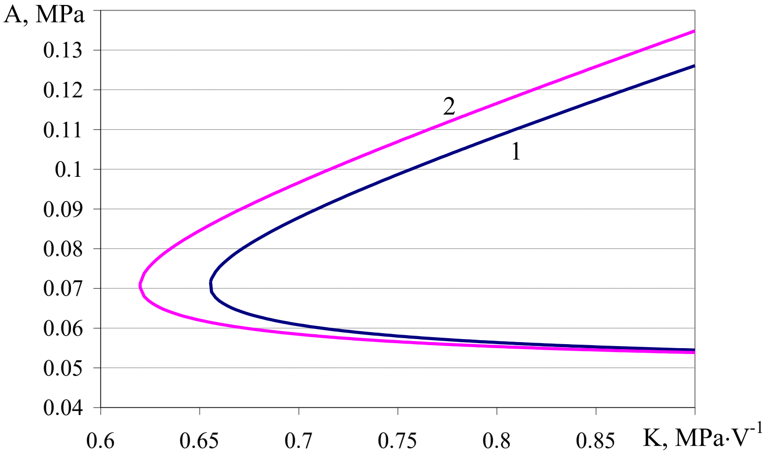

Fig. 6. Dependence $A = A(K)$: 1 – $\tau = 0.2$ s; 2 – $\tau = 2.0$ s

The lower parts of the graphic dependences shown in **Fig. 6** correspond to unstable periodic motion. It follows from the analysis of graphic dependences that there are critical values of the transmission coefficient $K_{\min}$, when exceeded, self-oscillations are possible in the subsystem. From (14) it follows that the value of $K_{\min}$ is determined by the expression:

$$K_{\min} = 0.25\pi\left(\tau_0 + \tau\right)\left(\tau_0\tau N\right)^{-1}. \tag{15}$$

Fig. 7 shows the dependence $K_{\min} = K_{\min}(\tau)$ at $\tau_0 = 12.75$ ms and $N = 10^{-4}$ V·(Pa)$^{-1}$.

The area that lies above the graph in **Fig. 7** corresponds to the self-oscillatory mode of operation of the pressure stabilization subsystem.

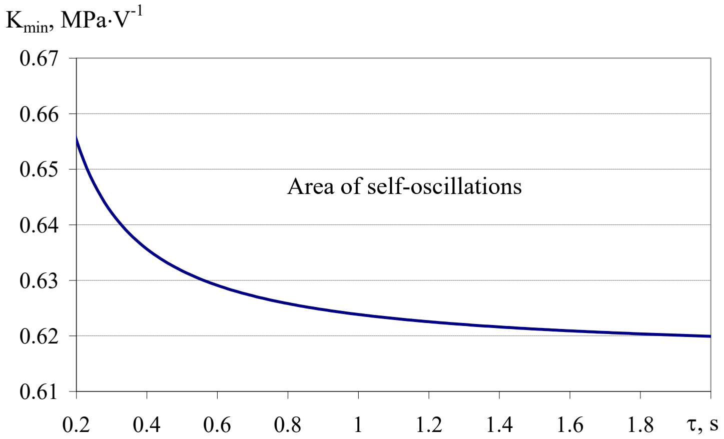

Fig. 7. Dependence of the critical value of the transfer coefficient on the parameter τ

The analysis of expression (14) indicates that it is fundamentally possible to provide a self-oscillating mode of operation in the hydrogen storage and supply system by varying the values of the parameters K or τ. Variation of the values of the parameter τ is a more difficult technical problem than variation of the values of the parameter K. In the latter case, the change in the value of the parameter K can be achieved by including an additional amplification stage in the control loop.

2. 2. 3. Gas generator control algorithm

The results obtained are the basis for the formation of an algorithm for controlling the gas generator of the hydrogen storage and supply system. The formation of such a control algorithm is preceded by the determination of the parameter $\tau_0$of the transfer function (2). For this purpose, the graphical dependencies shown in **Fig. 2, 3**.

The value of the parameter τ_0, as well as the values of the parameters τ, D and σ are the initial data for the formation of the gas generator control algorithm. Using the values of the parameters τ_0 and τ the frequency of self-oscillations ω_0 is chosen. For this, expression (12) or the graphic dependence shown in **Fig. 1** is used. 4. Then, using the graphical dependencies shown in **Fig. 5**, as well as taking into account the restrictions in the form of expression (15) or the graphical dependence shown in **Fig. 7**, the self-oscillation amplitude A and the value of the coefficient K_0 are determined.

The control algorithm for the gas generator of the hydrogen storage and supply system is reduced to the implementation of the following procedures:

– the hydrogen storage and supply system, by changing the value of the transfer coefficient of the linear part of the pressure stabilization subsystem to a value equal to K_0, is transferred to the self-oscillating mode of operation;

– determination of the parameters of the self-oscillatory mode of operation of the hydrogen storage and supply system – amplitude A and frequency ω_0;

– the values of the parameters A and ω_0 are compared with their a priori given values A_1 and ω_{01}, respectively;

– according to the result of comparing the values of the parameters of the self-oscillatory motion with their a priori set values, the result of the control of the gas generator is formed.

Fig. 8 shows a block diagram of a hydrogen storage and supply system in which such an algorithm for its control is implemented.

The scheme differs from the scheme shown in **Fig. 1** in that the amplifier is made of two parts 5.1 and 5.2. The gain of such an amplifier is designed to provide the value of the transfer coefficient of the linear part of this subsystem, equal to K_0. In this case, self-oscillations with parameters A and ω_0 will take place in the system. The frequency discriminator 7 serves to compare the frequencies ω_0 and ω_{01}, the amplitude discriminator 8 serves to compare the amplitudes A and A_1. The comparison results are processed in the information analysis block 9.

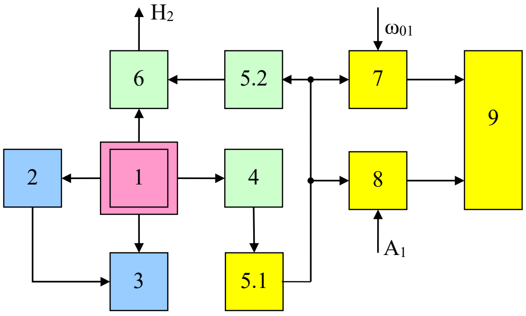

Fig. 8. Structural diagram of the hydrogen storage and supply system with control of its state

3. Results and discussion

The conducted studies on the development of an algorithm for controlling gas generators of hydrogen storage and supply systems made it possible to obtain the following results:

– the transfer function of gas generators can be approximated by the transfer function of the inertial link, the time constant of which lies in the range (11.5÷13.0) ms;

– the presence of a nonlinear static characteristic of the pressure sensor in the pressure stabilization subsystem predetermines the possibility of the existence of a self-oscillating mode of its operation in such a subsystem;

– the functional relationship between the parameters of self-oscillations – frequency and amplitude and the parameters of the pressure stabilization subsystem in the cavity of gas generators was determined;

– an analytical expression is obtained for the critical value of the transfer coefficient of the linear part of the pressure stabilization subsystem in the cavity of gas generators, which determines the region of existence of self-oscillations;

– to transfer the gas generator to a self-oscillating mode of operation, it is advisable to ensure that an additional amplification stage is included in its control circuit;

– to implement the control algorithm for the gas generators of the hydrogen storage and supply system, it is necessary to use self-oscillations in the pressure stabilization subsystem as a test effect. In this case, the controlled parameters are the parameters of the self-oscillatory mode of operation of gas generators.

The presence of nonlinearity in the pressure stabilization subsystem of the hydrogen storage and supply system opens up new approaches to the creation of control algorithms and its main element, the gas generator. One of these approaches is associated with the use of a self-oscillatory mode of operation of the hydrogen storage and supply system, which is a test mode. For a compact description of hydrogen generation processes, the transfer function of the gas generator is used, the characteristic polynomial of which is of the second order. The use of the criterion for the minimum absolute error of the mismatch of the reduced amplitude-frequency characteristics (3) makes it possible to lower the order of the characteristic polynomial of the gas generator transfer function. For the characteristic values of the parameters of the transfer function of the gas generator given in [15], its simplified expression (2) was obtained. At the same time, with a mismatch error not exceeding 5.0 %, the value of the time constant of such a transfer function belongs to the range (11.5÷13.0) ms. The minimum mismatch error is achieved when the gas generator time constant is 12.8 ms.

The nonlinearity of the pressure stabilization subsystem is due to the relay static characteristic of the pressure sensor, which predetermines the possibility of self-oscillations in such a subsystem. Using the harmonic balance equation, analytical expressions are obtained for the parameters of self-oscillations in the hydrogen storage and supply system – frequencies and amplitudes. At the same time, it should be noted that it is advisable to implement the self-oscillating mode of operation of such a system by increasing the values of the transfer coefficient of the linear part of the pressure stabilization subsystem. For the characteristic values of the parameters of the hydrogen storage and supply system, the region of existence of the self-oscillatory mode of its operation is constructed, which is shown in **Fig. 7**. It should be emphasized that the transfer of the hydrogen storage and supply system to the test mode of operation – self-oscillating mode, is carried out without the use of external equipment, but only by changing the value of its one parameter – the transfer coefficient.

The algorithm for monitoring the technical condition of the gas generator of the hydrogen storage and supply system includes switching it to the self-oscillatory mode, determining the parameters of these self-oscillations, and comparing the obtained values with a priori given ones. As a priori given values of the parameters of self-oscillations, the values determined with the help of analytical dependencies (12), (14) and (15) or with the help of graphic dependencies shown in **Fig. 4–7** are used. The technical implementation of the gas generator control algorithm can be implemented in the form given in [18].

It should be noted that the implementation of such an algorithm for monitoring the technical condition of the gas generator of the hydrogen storage and supply system assumes the absence of nonlinearities in the elements of its pressure stabilization circuit (except for the pressure sensor). Further research can be aimed at studying the influence of the nonlinear characteristics of the elements of the gas generator pressure stabilization circuit on the result of monitoring its technical condition.

4. Conclusions

A simplified mathematical description of the processes occurring in the gas generator is obtained, which is presented as a transfer function of the inertial link. It is shown that when choosing the value of the time constant of such a transfer function equal to (11.5÷13.0) ms, the mismatch error of the amplitude-frequency characteristics does not exceed 5.0 %.

Analytical expressions are obtained for the parameters of the self-oscillatory mode of operation of the gas generator – the frequency and amplitude of self-oscillations. Using these expressions, it is shown that for the minimum value of the time constant of the gas generator and typical values of the parameters of the pressure stabilization circuit, the frequency and amplitude of self-oscillations lie, respectively, in the range (7.0÷20.0) s^{-1} and (70.0÷130.0) kPa.

An algorithm for controlling the gas generator of the hydrogen storage and supply system has been developed, which is based on the transfer of this system to a self-oscillating mode of operation and the subsequent determination of its parameters – the frequency and amplitude of self-oscillations. The transition to the self-oscillating mode of operation of the hydrogen storage and supply system is carried out by changing the value of the transfer coefficient of the pressure stabilization subsystem, which exceeds the critical value. It is shown that for the characteristic parameters of this subsystem, the value of the critical value of the transfer coefficient belongs to the range (620÷655) kPa.

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