Multi-channel gas-diesel engine control system based on jet-convective sensors

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Abstract. Accurate measurement of the dynamic flow rate of the components of the gas-fuel mixture is required in electronic automatic control systems of the internal combustion engine. The paper substantiates the structural construction of the measurement channels of the multi-channel gas-diesel engine control system. In the implementation of the measurement channels, special attention is paid to the structure of the jet-convective channel for obtaining an informative signal on the gas fuel flow rate and the structure of the ion-labeled channel for measuring the air flow rate. Application of jet-convective transducers is supplemented by the original structural scheme of primary signals processing, which will allow expanding the measurement range towards low flow rate values, increasing the speed and reducing the random component of the error.

1 Introduction

One of the urgent problems of modern engine building is the increase of economic and ecological qualities of automobile transport. This is due to the fact that road transport emits into the environment more than 40% of the total mass of these pollutants entering the atmosphere from all sources of pollution, including industrial production, mining, etc.

Automotive electronic internal combustion engine control systems (ECS) largely determine the ecology of the environment, fuel economy, road safety and increased productivity by providing comfort in passenger car interiors and truck cabs.

The solution to the problem of fuel economy and reduction of environmental consequences from ECS operation, can be achieved by optimizing and adapting the working process in the ECS (reduction of fuel consumption), which correlates ultimately with the reduction of toxicity of exhaust gases and their impact on the environment and active safety of the vehicle. This is directly related to the need to improve the electronic automatic control systems (ACS) of the engine, transmission, chassis and optional equipment) [1-6].

Compliance with the requirements limiting the toxicity of exhaust gases and fuel consumption requires maintaining the stoichiometric composition of the combustible

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mixture, shutting off the fuel supply in the forced idling mode, precise and optimal adjustment of the ignition timing or fuel injection. In addition, it allows increasing: the throttle response of the engine, reliability of cold and its starting, accelerating the process of warming up and increasing the engine power. Direct measurement of engine torque (current load characteristic) on the car is associated with great technical difficulties, so the main load sensor are air flow sensors and (or) the pressure sensor in the inlet pipe.

To determine the engine crankshaft speed, a pulse counter from an induction-type crankshaft position sensor or from an ignition distributor sensor is usually used. The values obtained from the tables are corrected depending on the signals from the coolant temperature, throttle position, air temperature, on-board voltage and other parameters [2, 4, 7].

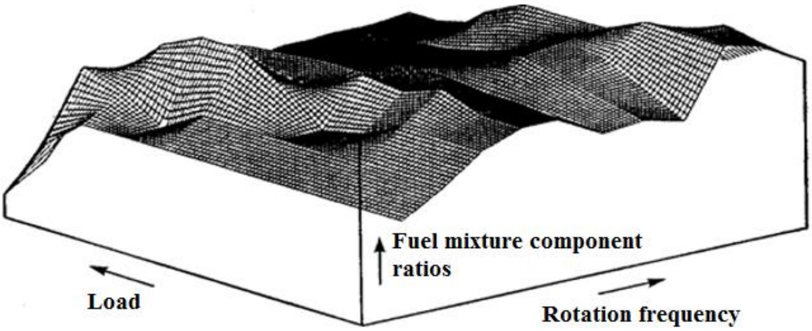

Fig. 1. Dependence of the ratio of fuel mixture components (excess air ratio) on load and engine crankshaft frequency

Adaptive control (feedback control) is used in systems with an oxygen sensor (λ-probe). The availability of information on the oxygen content in the exhaust gases makes it possible to keep the excess air coefficient $a(\lambda)$ close to 1. When controlling fuel injection by feedback using the control unit (CU), the pulse duration is initially determined by the load and engine crankshaft speed sensor data, and the signal from the oxygen sensor is used for precise correction. Fuel injection control by feedback is performed only when the engine is warmed up and within a certain load range.

The principle of adaptive control is also used to stabilize the idle speed of the crankshaft and to control the ignition advance angle by the detonation limit. Modern ECSs for gasoline and gas-diesel engines have a self-diagnostic function. The control unit checks the operation of sensors and actuators and identifies faults. When a malfunction is detected, the control unit memorizes the appropriate code and activates the *CHECK ENGINE* warning light on the instrument panel.

Due to the widespread use of automotive electronic control systems, "virtual" sensors, which are mathematical models of working processes in internal combustion engines and units, providing control and correction of parameters not subject to direct measurement of the control object parameters, are widely used. Intelligent sensors are widely used, which in addition to the sensing element have a built-in device for conversion of the sensor signal into a digital form. In promising and modernizing microprocessor control systems, artificial neural networks [8] are increasingly used to adapt the regulation program of the automotive electronic control system to changing operating conditions (system self-learning).

The technological variation in the characteristics of the elements of the ECS and the engine has a significant influence on the quality indicators of the engine operation. In order to compensate it and to take into account their changes during operation, the unit program provides a self-learning algorithm. As shown in a number of papers [9, 10], the signal from the oxygen sensor is used to adjust the value of the injection duration obtained by the specified table dependence in the ROM of the control unit. However, if there are significant discrepancies, such a process takes a long time. The self-learning consists in storing in the memory of the control unit the values of the injection duration correction coefficient. The entire engine operating range is generally divided into four characteristic learning zones: idling, high speed at low load, partial load, high load. When the engine runs in any of the zones, the injection pulse duration is adjusted until the actual fuel mixture composition reaches the optimal value.

The correction coefficients thus obtained characterize the specific engine and participate in the formation of the injection pulse duration in all modes of its operation. The adaptation process is also used to control the ignition advance angle in the presence of detonation feedback. The main problem with the adaptation algorithm is that sometimes an incorrect sensor signal can be perceived by the control system as an engine parameter change. If the error in the sensor signal is so small that a fault code can be detected and recorded, the fault may go undetected. In some variants of the ECS design, however, the correction factor values are not saved when the control unit is de-energized. Realization of this project on the basis of built-in microcontrollers and their interfacing with the central on board PC allows to provide documentation of the results of measurement and control of the parameters of the gas mixture components, as well as their indication.

2 Materials and methods

The dynamic development of the car fleet in Russia (10% per year in Russia) and other countries is accompanied by an increase in the consumption of liquid fuel (gasoline, diesel fuel), which leads to significant environmental consequences. Use of natural gas as fuel reduces emissions of harmful substances by 1.5...1.75 times, besides there is a 77...80% reduction of fuel consumption and 40...50% increase of the engine life [11, 12].

In addition, the use of natural gas as fuel makes it possible to improve the process of controlling the operation of a vehicle engine and necessitates the development and coordination of sensors and meters of fuel flow parameters and working fluid state parameters used in complex electronic control systems of the engine, transmission, brakes, etc. An important role in the control process has information about the value of air flow and the amount of gas fuel consumed. Therefore, for the first time, two modules (position 12 and 19) for measuring the flow rate of each of the two components of the fuel mixture: gas fuel and air, are introduced into the ECS structural diagram presented in Figure 2. The informative signals from the gas fuel flow rate sensors go to the control unit (position 6), where they are processed and an output signal proportional to the ratio of the current gas-air flow rates is generated, which is a measure of the air excess. This makes it possible to optimize the engine operation process according to the set program, taking into account the selected engine mode. This is done by sending control signals to the throttle (position 5) and ignition coil (position 13).

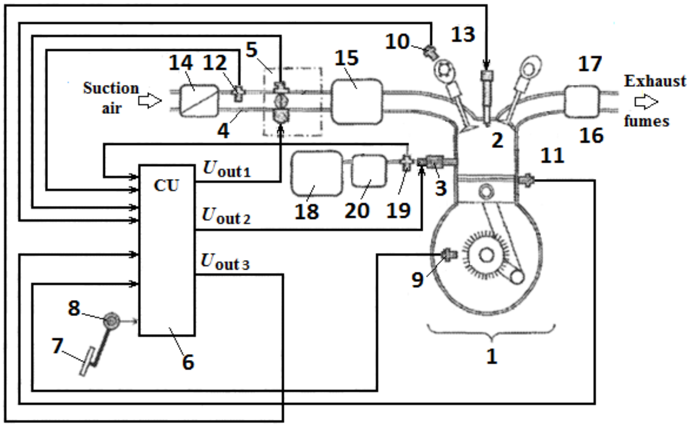

Fig. 2. Structural scheme of the electronic control system for the gas-diesel engine: 1 – internal combustion engine; 2 – spark plug; 3 – fuel injection valve; 4 – air intake duct; 5 – throttle with electronic control; 6 – engine control unit; 7 – accelerator pedal; 8 – gas pedal position sensor; 9 – crankshaft angle and speed sensor; 10 – cam angle sensor; 11 – detonation sensor; 12 – air flow module; 13 – ignition coil; 14 – air cleaner (air filter); 15 – expansion tank; 16 – exhaust manifold; 17 – catalytic converter; 18 – fuel tank; 19 – gas fuel flow module; 20 – gas reducer

The proposed scheme of the engine ECS dictates the need to develop and study sensors of flow meters and gas fuel meters on vehicles of various applications. It is important to note that the efficiency of engine operation in various modes of its operation is determined by the ratio of the components of the gas-fuel mixture (gas fuel - air) (Fig. 1). In this regard, the purpose of the work is to justify the principles of the structural design of the information channels of ECS. Expanding the composition of channels for measuring the flow rate of gas fuel components will significantly improve the efficiency and environmental friendliness of gas-fueled automobile engines, as well as ensure the reliability and safety of the control and management processes of gas-diesel engines.

A distinctive feature of the ECS structure implemented in the project is the use of jet convective transducers as part of the measuring complex to control the flow rate and quantity of gas fuel, and the use of ion-metering transducer to control the air supply [13, 14].

3 Results and discussion

In Russia and abroad intensive work is carried out to create sensors and meters of parameters of flow rate and quantity of gaseous components of the fuel mixture. The known flow meters of gaseous components of the fuel mixture are manufactured by BROOKS INSTRUMENTS B.V. (Italy), KOBOLD MESSRING GmbH (Germany), KROHNE (UK), Bosch (Germany), Mitsubishi, Hitachi Ltd. (Japan), General Motors Corp. (USA), Lukas Ltd. (UK), etc. While preserving the advantages of technical characteristics, the cost of the proposed modules for measuring fuel mixture component flow rate is less than the cost of devices from foreign companies, in addition, it is expected to master their production with direct author supervision in Russia and thereby significantly weaken the shortage of automotive sensors and electronic components in domestic manufacturers of automotive electronics.

Analysis of the principles and schemes of construction of modern automobile flowmeters and meters, implemented on the basis of thermal effects [15-17], allows the following main trends to improve the design and circuit solutions: introduction of a bypass channel to place in it the ASE of the primary converter; used as ASE wire, film and semiconductor thermoresistors (SCT), working in most cases at constant temperature mode; use in the design of channels and use in the design of flow measurement channels the principles of construction based on a combination of the dynamic differential method and the thermal method. It should be noted that in operating conditions, typical for cars, the immobility of all elements of mass flow meters is especially important. This requirement is satisfied to the greatest extent by flow meters based on thermal effects with the use of the jet-convective transducers (JCT). Among the main advantages of this group of meters are: small influence of pressure and temperature of the controlled fuel, the possibility of use at multistage reduction of gas fuel pressure, high accuracy, sufficient for effective regulation of gas fuel or air supply processes in case of liquid fuel combustion engines operation. Besides, design solutions of such gauges are characterized by high tightness, corrosion resistance, small size and weight. The wide list of JCT advantages makes them the most promising for application in electronic engine control systems.

The principle of operation of the gas fuel flow meter, built with the use of the JCT, is based on the dependence of the thermal power dissipated by the heated element from the flow of the flow that washes it [18]. Consequently, the thermal energy required per unit time to maintain a constant temperature difference between the heated element and the gas that washes it, is directly proportional to the mass flow rate through a given flow cross-section.

In the development of the module for measuring the mass flow of fuel components, despite the slight complication of algorithms for processing the primary informative signals, is the use of methods based on the use of a combination of different physical effects and principles of structural construction of processes of measuring transformation of mode parameters of automobile engine operation. A fundamental novelty in construction of the jet-convective module for measuring the gas fuel flow rate is the use of a new combination of basic physical effects (deformation of the gas flow in the jet and jet-convective interaction of the gas flow with the heated body), which allows expanding the measuring range of the flow rate of the measured medium by more than one order compared with the known analogues [18-20].

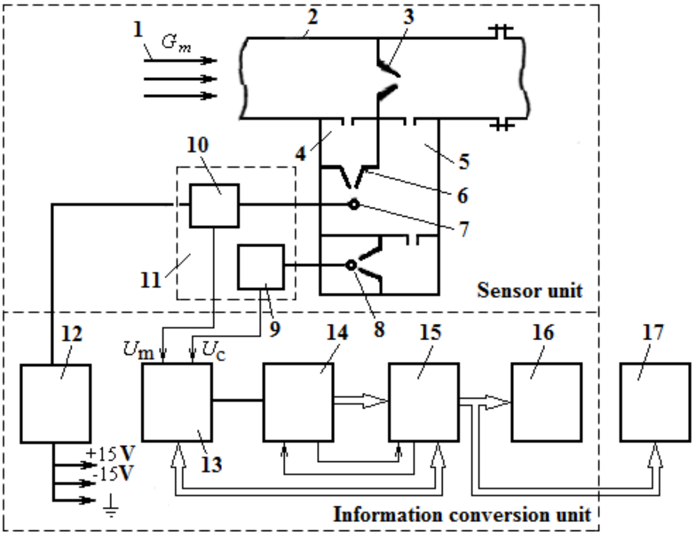

Fig. 3. Structural scheme of a jet-convective gas fuel flow measurement module: 1 – measured flow of gas fuel; 2 – measuring channel of fuel equipment; 3 – narrowing device (ND); 4, 5 – pressure cavities before and after ND; 6 – forming nozzle; 7 – measuring anemosensitive element (ASE); 8 – compensating ASE; 9, 10 – schemes of switching on measuring and compensating ASE; 11 – board of switching on ASCE; 12 – power supply unit; 13 – measuring comparison scheme; 14 – ADC; 15 – information processing unit; 16 – information displaying system; 17 – electronic documenting system

In order to reduce the temperature error of the SCS, which has additive and multiplicative components, the jet-convective flow measurement module uses a differential method of conversion, in which the output signals of the measurement and compensation measurement channels respectively have output voltages:

measurement channel output voltage

$$U_m = \sqrt{r_T \Delta T_m} \sqrt{H_{0m} + \gamma \sqrt{G_m / F}} \tag{1}$$

output voltage of the compensation channel

$$U_c = \sqrt{r_T \Delta T_c} \sqrt{H_{0c}} \tag{2}$$

where $r_T = A \exp\left(B/T\right)$ – resistance of measuring and compensating ASE; A and B – mode parameters of the anemosensitive element; ΔT_m, ΔT_c – overheating of measuring and compensation ASEs; H_{0m}, H_{0c} – dissipation coefficient of measuring and compensating ASEs; γ – anemosensitivity coefficient, equal to

$$\gamma = \frac{\left(H_1 - H_2\right)}{\sqrt{\rho / F}\left(\sqrt{G_{m1}} - \sqrt{G_{m2}}\right)} \tag{3}$$

where H_1 and H_2 are power dissipation coefficients, proportional to the corresponding values of the mass flow rate G_{m1} and G_{m2}; ρ – density; F_c – the cross-sectional area at the outlet section of the forming nozzle of the anemosensitive module.

Taking into account the chosen method of measurement and the need to reduce the temperature errors of the meter, the output signal should be formed on the basis of the dependence

$$\delta_\varepsilon = \frac{U_m^2 - U_c^2}{U_c^2} \tag{4}$$

Experimental studies of the prototype (fig. 4) allowed us to obtain a graph of the output characteristic (fig. 5) and to estimate the reduced error of gas fuel flow measurement (fig. 6).

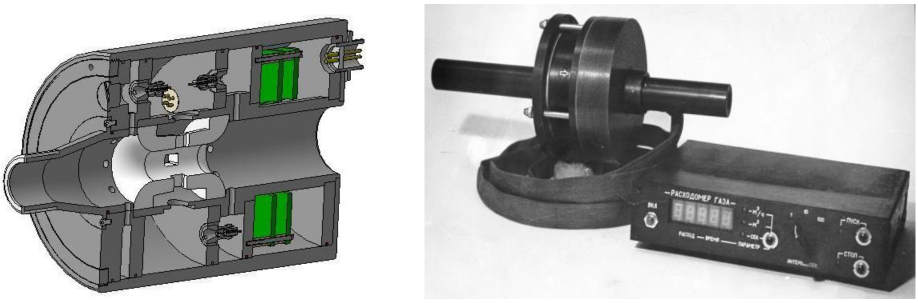

Fig. 4. 3D model of the gas fuel measurement module and general view of the prototype of the gas fuel measurement module

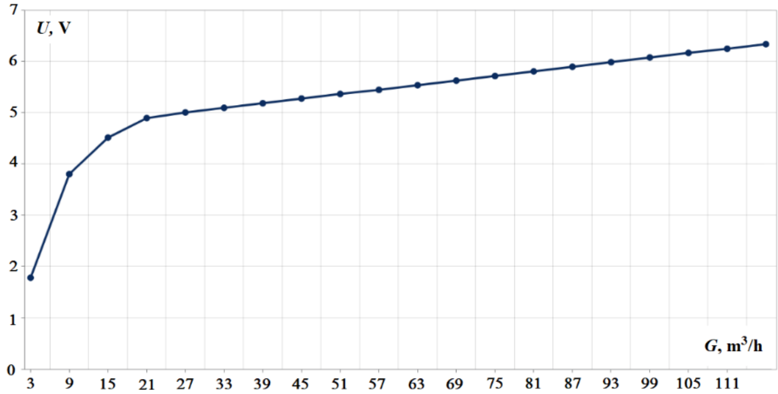

Fig. 5. Graph of the output characteristic $U = f(G)$

The analysis of the experimental results showed that the output characteristic $U=f(G)$ has a generally nonlinear character and can be divided into two sections with nearly linear conversion functions

$$U(G_V) = 0{,}51G_V + 0{,}12 \tag{5}$$

in the range up to 16 m^3/h and a relative reduced error not exceeding 1,5%

$$U(G_V) = 0{,}016G_V + 4{,}65 \tag{6}$$

in the range 16...115 m^3/h and a relative reduced error not exceeding ±0.5%.

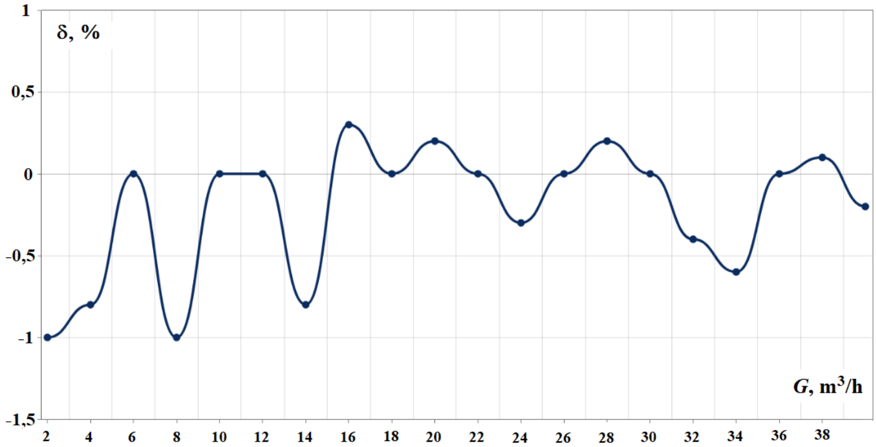

Fig. 6. Graph of the reduced error of flow measurement

In the first range, the investigated prototype of the module for measuring the parameters of gas fuel due to its high sensitivity can work successfully in control devices, and in the second range, due to the greater linearity of the output characteristic, it can be used as a measuring device in a much wider range of flow rates [21].

Ion-label transducers belong to a large class of kinematic means, implementing in the input to the measured medium a natural local inhomogeneity of any medium parameter, excluding pressure losses on the interaction with measuring elements [22-24].

The time-of-flight method of airflow measurement is used in experimental flowmetry. In this case, different types of tags by their physical nature are used. These are thermal, optical, radioactive, magnetic, ionic and other types of inhomogeneities [19, 25].

Selection of the tag type is carried out on the basis of the specific measurement task, taking into account the properties of the controlled environment, the flow velocity measuring range, influencing destabilizing influences and other factors. To register the moment of passage of the marking electrodes in most cases, mainly three types of output signals are used: by frequency, by time interval and by phase shift. In the present development it is proposed to build the airflow measurement module on the basis of the following structural scheme (fig. 7), the output signal of which is frequency [26].

Its basic circuit is the presence of a label recorder with a generator through a control circuit and a voltage-controlled oscillator (VCO). The generator is a series-connected integrator and a pulse filter [27-29].

The ion-tagging module of air flow measurement contains a flow-through receiver, a tag generator, which includes a spark gage 2 connected to the high-voltage pulse generator 1, which is triggered by the generator controlled voltage 9. The generator 9 in addition to the control output has an information output, from which the signal in the form of pulse frequency F is taken.

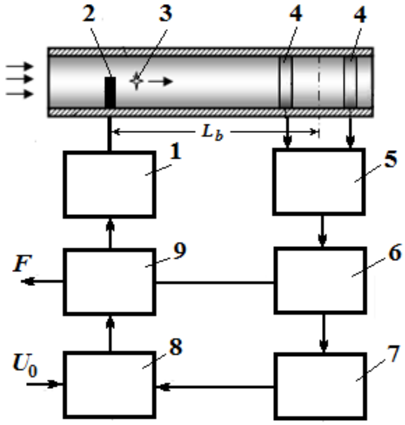

Fig. 7. Structural scheme of ion-measuring airflow module

Receiver tags 4 is remote from the arrester 2 at a distance L_b and connected via a label recorder 5 to the pulse shaper 6, the second input of which is connected to the generator 9. As a shaper of rectangular pulses it is advisable to use RS trigger. The output of the trigger is connected to the integrator 7, the role of which can be performed by an integrating RC circuit with a large time constant. The output of integrator 7 is connected to the first input of the comparator 8, to the second input of which the reference voltage U_0 is supplied. The output of the comparing device is connected with the control input of the generator 9.

The tag from arrester 2 is carried away by the flow. When the tag passes near the receiver 4, a pulse is formed at the output of the recorder 5, which goes to the shaping unit 6. At the other input of the shaping unit at the moment of mark creation a pulse from the generator 9 is received. At the output of the shaper 6 pulses of rectangular shape are formed, the leading edge of which corresponds to the moment of mark generation, and the trailing edge corresponds to the moment of mark registration by the receiver, and the pulse duration is determined by the ratio $\tau = L_b / V$. These pulses are fed to the input of the integrator 7, where the constant component of the voltage U_{int} of the pulse sequence is allocated. This voltage goes to the input of the comparison device 8, the output of which forms the voltage of the difference between the constant component and the voltage U_0, which determines the set threshold level. Under the influence of this voltage the generator frequency is changed 9 so that the difference ($U_{\text{int}} - U_0$) is compensated to zero by changing U_{int}. At zero value of the difference ($U_{\text{int}} - U_0$) provides the generation frequency, at which the equality is fulfilled

$$U_{\text{int}} = U_0 = \frac{A_0 \tau}{T_t}, \tag{7}$$

where A_0 – pulse amplitude.

The dependence of the output frequency at the generator 9 output on the flow rate is determined by the following relationship

$$F = G_v \frac{U_0}{A_0 L_b}, \tag{8}$$

The frequency of label generation depends linearly on the flow rate, and the slope of this dependence is determined by the ratio $\frac{U_0}{A_0 L_b}$, which can be easily changed in a wide range by adjusting the value of U_0 or A_0.

Experimental studies of the prototype of the ion-measuring module of air flow measurement allowed us to determine the conversion function (fig. 8), the analysis of which allowed us to distinguish 2 linear sections. The first section is in the range of 6-30 l/min, and the second section in the range from 40 -150 l/min, which differ significantly in steepness.

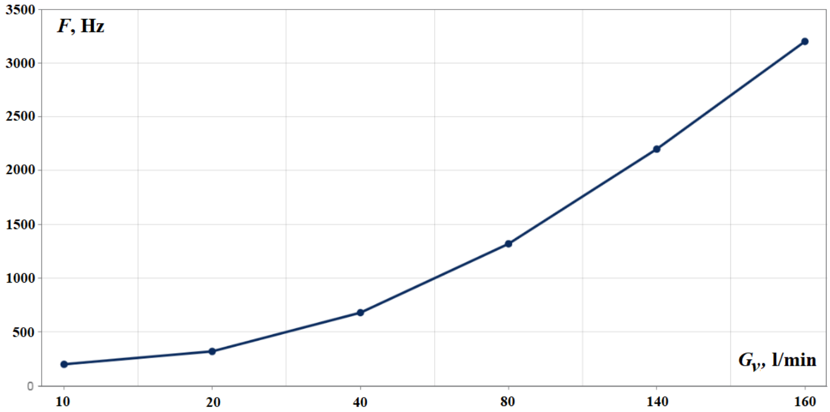

Fig. 8. Graph of the output characteristic $U = f(G_V)$ of the prototype airflow ion-measuring module

4 Conclusion

The structural construction of the air flow rate and gas fuel mass flow rate measuring channels proposed in the ESAU, compared with the existing analogues, has expanded functionality: it allows measuring several parameters: volume flow rate, mass flow rate and gas fuel density; distinguished by increased stability, reliability and stability of operation under conditions of application on moving objects due to the use of the principle of structural redundancy.

The results of studies and tests of mock-up samples of jet-convective and ion-metering modules for measuring the flow rate of gas fuel and air supplied to the car engine have confirmed their performance in the range of measured flow rates.

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