Elements and devices of automatic control systems. Primary transducers (sensors).

1. *Introduction. The concept of sensor.*

Human's eyes perceive the shape, size and color of surrounding objects, ears hear, nose smells. Usually there are distinguished five kinds of sensations associated with vision, hearing, smell, taste and touch. For the formation of sensations, a person needs external stimulation of certain organs - "sense sensors". For different kinds of sensations, certain sense organs play the role of sensors:

Vision......Eyes

Hearing........Ears

Taste........Tongue

Smell....Nose

Touch....Skin

However, only sense organs alone are not enough for the feeling. For example, visual sense does not mean that a person sees only with eyes. It is well known that irritations from the external environment in the form of signals are transmitted through eyes along the nerve fibers to the brain and it is there where the impression of large and small, black and white, etc. are formed. This general scheme of sense formation applies also to hearing, smell and other senses, that is, in fact, external stimuli as something bitter or sweet, quiet or loud are evaluated by the brain, which requires sensors that respond to these stimuli. The world around us can be divided into two parts: nature and objects created by man.

A similar system is formed in automation as well. The control process is to receive information about the state of the control object, its control and processing by the central unit and the issuance of control signals to execution devices. Sensors of nonelectrical quantities serve for the formation of information. Thus, temperature, mechanical displacement, presence or absence of objects, pressure, flow of liquids and gases, speed of rotation, etc. are controlled.

A sensor is a technical means that perceives the impact of the object of interest and responds by changing the output signal.

A signal means a physical process, which can be converted and transferred via transmission lines to the consumer of information who is interested in the state of the object.

Signals can be described by the following characteristics or a set of them: amplitude, frequency, phase, spectral composition, or digital code.

Thus, each sensor is characterized by a set of input parameters (of any physical nature) and a set of output electrical parameters. Output signals of electronic sensors may be voltage, current or charge, which can be described by amplitude, frequency, phase, or digital code. The output signals of optron sensors can be the intensity, spectral composition, which are described by amplitude, frequency, phase, spatial distribution or digital code.

Any sensor is a converter of energy. Regardless of the type of a measured value, there is always the transfer of energy from the test object to the sensor. Sensor operation is a special case of the transformation and transmission of information, and any information transfer relates to the transfer of energy.

The structure of the sensors includes at least one primary transducer and several measuring transducers.

Primary transducers are built on physical phenomena, allowing direct transformation of energy of external influence into the signals or properties of the physical environment in which the signals are formed.

Measuring transducers transform signals of the primary transducer into signals suitable for transmission of the measuring information.

For example, a chemical sensor may include two transducers (figure 1), one of which (the primary transducer) converts the energy of chemical reactions into heat and the other one, a thermocouple, converts heat into an electrical signal. The combination of these two measuring transducers is a chemical sensor — a device that produces an electrical signal in response to a chemical reaction.

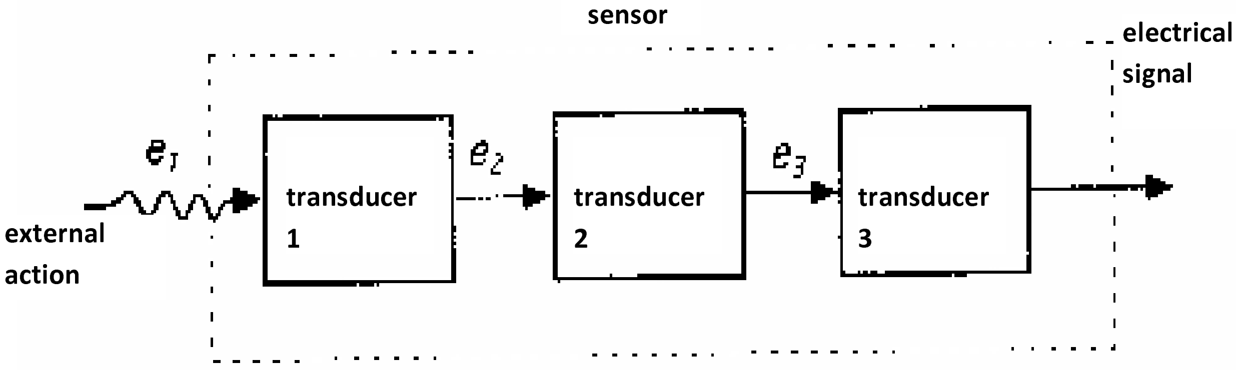

Figure 1 – block diagram of a sensor

All sensors can be divided into two categories: passive and active.

A passive sensor does not need any additional energy source. Most of passive sensors are direct acting devices (for example, a mercury thermometer).

An active sensor requires external energy for its operation. Since these sensors change their characteristics in response to changing of external signals, they are sometimes called parametric sensors (e.g., resistance temperature devices).

In fact, active sensors convert the changes of their internal characteristics into electrical signals, i.e. certain parameters of the active sensors modulate excitation signals and this modulation carries information about the measured quantity. For example, thermistors are temperature sensitive resistors. The thermistors themselves do not produce any electric signals, but when electric current (the excitation signal) is passing through them, their resistance can be determined by changing of the current and/or voltage drop across them. The resistance value (in ohms) shows the measured temperature, which can be found on the known relationships. Another example of an active sensor is a resistive strain gauge, whose electrical resistance depends on the magnitude of its deformation. It is also necessary to pass the electric current from an external power source through the sensor to determine its resistance.

Depending on the choice of a reference point, sensors can be divided into absolute and relative ones.

An absolute sensor detects an external signal in absolute physical units (thermometer) that do not depend on the conditions of measurement, whereas the output signal of a relative sensor can be interpreted in different ways in each case. An example of an absolute sensor is a thermistor. Its electrical resistance directly depends on the absolute temperature on the Kelvin scale.

As for the relative sensor, (thermocouple) voltage at its output is a function of the temperature gradient on the wires of the thermocouple. Therefore, it is possible to determine the specific temperature on the output signal of a thermocouple only with respect to a known reference point.

Types of signals, their constituents, signal carriers, their informative parameters and types of informative signal at the output of the sensor-converter

Φ = (x, y, z, t) signal	Φ signal carrier	Information parameter of P signal	Type of signal at output of sensor-converter
Temporary Φ = *f(t)* (form used mainly for signal transmission): - continuous - discontinuous *Spatial* Φ = *f(x, y, z)*, (form used mainly for storage of signals: - one-dimensional Φ = *f(x)* - two-dimensional Φ = *f(x, y)* - three-dimensional Φ = *f(x, y, z)*	*Mechanical* (speed, acceleration, force, mass, pressure, work, etc.) *Geometric* (length, thickness, angle, area, volume, height, printing signs, etc.) *Hydraulic* (pressure, pressure differential, flow rate, etc.) *Pneumatic* (pressure, pressure differential, gas flow rate, etc.) *Acoustic* (sound intensity, pitch, etc.) *Thermal* (temperature, heat quantity, etc.) *Magnetic* (inductance, magnetic field strength, magnetic flux, etc.) *Electrical signal* (current, voltage, power, etc.) *Optical* (brightness, refraction index, wavelength, etc.) *Nuclear and physical* (neutron flux density, etc.) *Chemical signal* (pH, gas concentration, etc.)	Amplitude Frequency Phase Number of pulses Pulse duration Pulse sequence Pulse position Number of points Point spacing Distance between points and origin of coordinates Point spacing Distance between points and origin of coordinates	*Analog* (P can take any value within the specified range) *Discontinuous* (P can take only final values): - binary (P can take only two values); - digital (P values correspond to words of conditional alphabet) - multi-point (discontinuous without conditional alphabet) *Continuous* (P may change at any time) *Discontinuous* (P can change only at certain moments of time)

2. *Classification of sensors*

There is a great variety of sensor types. Some of them are shown in table 1.

Table 1 – Sensor properties

No	Controlled variable	Form	Range of controlled variables
1	pressure	air	10…160 MPa
		liquid	
2	temperature	air	-40…+100 deg. C
		liquid	
		machine components	
3	humidity	air	0-100%
		free-flowing components	

4	level	liquid	over 0,5 m
		free-flowing components	0,01 – 100 m
5	concentration	explosive dust in air	micron size
		particles in liquid	micron size
		explosive dust in air	nano size
		particles in liquid	nano size
6	size of component grains	in liquid	micron size
		in air	micron size
		in liquid	nano size
		in air	nano size
7	electrostatic stress	in air	up to 5000 volts per meter
8	flow	liquid	
		gas	
9	mass	free-flowing measured material	
10	counters	transported elements	
11	spatial displacement of actuating elements	linear microdisplacement	1…2 micron
		angular microdisplacement	1 gr/m
		linear microdisplacement	0…5000 mm
		angular microdisplacement	0…360 gr
		rotation velocity	0…6000 r/min
12	deformation of surfaces and containers		
13	supply voltage magnitude of actuating units		6…110 kV
14	supply current magnitude of actuating units		1…100 kA
15	radiation		
16	composition of mixtures	gas	
		liquid	
17	elements of secondary converters in integrated form	gradient two-dimensional deflectors (KDP)	±0,3..0,5°, 200 khz, 5,5 kV
		planar one-dimensional deflectors (LCD)	±3..30°, 0,5 khz, 20 V
		diffractive two-dimensional deflectors	±1..2°, 1..15 MHz, 50 V

		diffractive planar deflectors	±6°, 200 MHz, 10 V
		controlled diffraction spectrometers	band 200..300 nm, resolution 1..2 nm, 1..15 MHz, 40..50 V
		uncontrolled integrated spectrometers	band 60 nm, resolution 0,5 pm, repeatability 5 pm, supply 5 V
		multichannel diffraction modulators of Raman-Nath	depth of modulation 99,5%, frequency 15 MHz, voltage 50B
		single-channel integrated modulators of Mach-Zehnder	depth of modulation 99,7%, frequency 500 MHz, voltage 25V

Some examples of sensors.

Linear/angular displacement sensors produce a signal proportional to the magnitude of the displacement of the object from one point in space to another one (inductive, optical, resistive, etc.).

Linear/rotational motion speed sensors produce a signal proportional to the speed of displacement of the object from one point in space to another one (inductive, optical, Doppler effect, etc.).

Acceleration sensors transform the action of inertial forces arising from the acceleration of bodies with mass with the use of elastic elements into an electrical signal (piezoelectric, fiber optic, etc.).

Temperature sensors produce the voltage proportional to absolute temperature (absolute measurement) or temperature difference (relative measurement) between a hot and a cold element (thermocouple).

Static or dynamic-pressure sensors convert deformation of flexible membranes that bend with the pressure change, into small displacement.

Proximity sensors on the conveyor line (optical, inductive, contact).

Sensors for the protection of dangerous perimeters (fiber-optic, capacitive, inductive, etc.) control the presence of a person in hazardous area.

3. Main characteristics of sensors

Sensor sensitivity is the ratio of the increment of the output signal of the sensor to changes in input informative parameter (signal).

Operating range is the range of variation of the input informative parameter, in which the sensor performs a transformation of the informative parameter with acceptable error.

Sensor resolution is the number of reliably distinguishable gradations of the informative parameter that can be recorded on the sensor output.

Conversion error is the absolute or relative deviation of the result of the information conversion by the sensor in the operating range.

The main causes of the errors are following:

1. The influence of the sensor on the object. (This error can be evaluated only when the object is known).
2. Technological deviations of the design parameters from their nominal values. Design parameters include material properties, dimensions of parts, assembly quality, parameters of electronic components.
3. The impact of environmental factors (temperature, humidity, atmospheric pressure, dynamic error, as it depends on the rate of change of the measured value, etc.).
4. The hysteresis of the conversion function.
5. The quantization of the output signal, if the sensor performs the code modulation.

6. The inaccuracy of the calibration.

There are the following types of errors.
On the presentation form, errors are divided into: absolute, relative and conventional (reduced).

The absolute error Δ of the measurement, expressed in units of the measured value, is represented by the difference between the measured and the true (actual) values of the measured value:

The relative error is represented by the ratio of the absolute error to the true (actual) value of the measured value and expressed in percent or fractions of a measured value:

The conventional (reduced) error (of a measuring instrument) is the ratio of the absolute error to the fiducial value (operating range):

Depending on the causes and places of occurrence, the errors are divided into instrumental and method.

The instrumental error is the total error of the applied measurement tool.

The method error is subject to the imperfection of the applied measurement method - the error of the adopted model of measurement, method of application of the measuring tool, algorithms, by which the result of measurement and other factors, not related to properties of the used measuring equipment, are computed.

The error of a measuring instrument, defined under normal conditions, is called the basic error.

The error due to the change in output values of the sensor as the result of the deviation of the measurement conditions from normal is called additional. It is accepted to distinguish additional errors on individual influential values (additional temperature error, additional error due to changes in atmospheric pressure, etc.).

The static error is an error that does not depend on the rate of change of the measured value. The static error of a measuring instrument occurs when the constant value is being measured with it.

The dynamic error is an error determined by the rate of change of the measured value over time. The occurrence of the dynamic error is due to the inertia of the elements of the measuring circuit of the measuring instrument, i.e. the fact that transformations in the measuring circuit do not occur instantaneously, but require some time. The dynamic error of a measuring instrument is the difference between the error of a measuring instrument in dynamic conditions and its static error corresponding to the value of the quantity in the given time.

The totality of all relevant factors, including external, forms the total error band.

The random component of the total error is a component of the measurement error, changing randomly (in sign and value) in a series of repeated measurements of a physical quantity of one and the same size, conducted with equal care in the same conditions.

The systematic component of the total error is a component of measurement error that remains constant or changes regularly in repeated measurements of the same physical quantity.

The components of total error are divided into additive and multiplicative.
One way to determine components of the total error is their definition with the appropriate sensitivity, which is expressed through partial derivatives of the output signal of the sensor to interfering factors.
So, the coefficient describing the impact of the influencing factor x_i on the sensitivity S of the sensor is determined:

$$k_i = \frac{\partial S}{\partial \beta_i}.$$

Then the general formula of the total error has the form:

$$\sigma_\Sigma = \sqrt{\sum_{i,j} r_{i,j} \cdot \sigma_i \cdot \sigma_j},$$

where $r_{i,j}$ – cross-correlation coefficient, σ_i, σ_j, - i and j components of error.

If the error components are not correlated, then the total relative random error δ_c can be determined:

$$\delta_c = \frac{1}{Y(x)} \sqrt{\sum_{i=1}^{n} \left[\frac{\partial Y(x, \beta, t)}{\partial \beta_i \cdot Y(x)} \cdot \Delta_{ci} \right]^2},$$

where Δ_{ci} – absolute deviation of i influencing factor, β_i – i influencing factor.

When calculating limiting error of the transducer δ_Σ, the numerical value of measurement error from all components (systematic and random) is determined and the summation is made:

$$\delta_\Sigma = \sum_{i=1}^{m} \delta_{mCCИC} \pm \delta_C,$$

where "+" or "-" signs are put on the condition that systematic and random errors are summed modulo; $\delta_{mCИCT}$ – m component of the systemic error.