Development of computer-aided design system of sensitive elements of control and automation systems

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Abstract. The subject of research is the element base of devices of control and automation systems used in modern weight- and force-measuring devices, in particular, consisting of annular elastic sensitive elements. The developing of annular elastic sensitive elements is based on the analysis of existing methods for calculating elastic elements, new algorithms and modified methods for calculating. The proposed automated methods for analyzing the statics and dynamics of the element base under investigation are based both on analytical methods of the classical mechanics of elastically deformed bodies and on numerical methods for the purpose of exploiting their advantages and compensating for the weaknesses. For the development of automated design systems for annular elastic sensitive elements, mathematical modeling of deformation processes in a solid was carried out and an analysis of their characteristics was carried out using the modern ANSYS software complex on the basis of the finite element method. The mathematical model of the annular elastic sensitive element has a high degree of adequacy, low laboriousness with high productivity and low time costs. The software package is based on generating the most geometric model, as well as creating nodes and elements. When calculating the frequencies and forms of free oscillations, a modal analysis is used for linear systems. The solutions obtained were refined by means of harmonic analysis and analysis of transient processes.

The article proposes a new approach to calculate and design the force-measuring membrane elastic element of the force sensor used in industrial scales with modern computer simulation methods. The reasons for the sensor error are described. The possibility of reducing the nonlinearity of the elastic characteristic and hysteresis due to the geometric nonlinearity and dry friction in the supports is considered. Rational geometric parameters of the elastic element were determined by the methods of finite element modeling, which make it possible to significantly reduce measurement errors. The research results are implemented in the practice of calculating and designing real structures.

The results of the dynamic calculation were compared with the experimental data. For this purpose, were used the bar-and-pic chart of application of load of the elastic sensitive elements. The developed system of computer-aided design of sensitive elements of annular elastic elements will allow to ensure the production of modern and competitive domestic element base of automation devices.

1. Introduction

Modern production of automation devices with a wide range of transducers and various types of sensors is characterized by an ever increasing growth of automation processes, which in turn ensures an increase in labor productivity. The development of automation leads to an increase in the efficiency of technical systems that include computing and control devices [1]. An example of such systems can serve as an
automated process control system for shipbuilding, automotive, metallurgy, chemical and other types of industry, which include the weighing of goods, sorting and transportation of products. Therefore, the development of modern weighing equipment that provides not only measurements of the object mass (weighing with the necessary accuracy and speed), but also automatic control, monitoring and regulation of technological processes, becomes the main direction in the design and production of weighing and dosing means. To do this, when designing annular elastic elements (AEE), the implementation of two-way communication with a computer is necessary, which allows remote control and adjustment of the control process. Modern automatic control systems are an important part of complex automation in various branches of precision instrument and mechanical engineering [2, 3].

The main task in the design of AEE is to achieve the required measurement accuracy. High requirements are imposed on the accuracy of AEE. The design of the elastic element has a significant impact on the measurement accuracy. As is known [1], the metrological error of the elastic element is determined by the dependence of the physicomechanical properties of the material on temperature, which for the type of sensor in question reaches 0.03% per 1 °C temperature change, as well as geometric nonlinearity (up to 0.3%).

The sensitivity of the elastic element substantially depends on the places of the strain gauges. In this case, such an arrangement of strain gauges is considered rational, in which one sensor is in the stretching zone and the other in the compression zone. In this case, it is desirable that the values measured by the strain sensors are equal in absolute value.

The composition of piezosistive microsensors of pressure includes elastic membrane sensitive elements (UMCE), which respond to changes in mechanical and temperature loads. These elements are in direct contact with the viscoelastic adhesive layer, which leads to the need to take into account their nonlinear properties. The viscous adhesive layer provides the transfer of the UMCE not only to the useful signal (measured pressure), but also interference caused by mechanical and temperature loads, which lead to deformation changes of the resistance strain gages and an increment of their resistances [1].

Existing developments of electrical measuring equipment allow the transformation of the measured value with the required degree of accuracy. However, with the low quality of the AEE, which are part of the measuring devices, it is impossible to achieve high accuracy of the measuring device as a whole. Although a magnetically adjustable arrangement is quite simple details, and many of them have been known and widely used for many centuries, their performance characteristics today do not satisfy their requirements in terms of accuracy, sensitivity, and other metrological characteristics [4,5,6].

A strain gauge force sensor (SGFS) is an elastic element that undergoes deformation under the action of a force. In specially selected areas of the element are glued sensitive elements - strain gauges. Structurally, modern strain gauges are a sensitive element in the form of a loop-like lattice, which is attached to the elastic element with the help of glue.

Sensitive elements are usually made of thin wire, foil, and can also be formed by vacuum deposition of a semiconductor film. To enable the sensitive element in the electrical circuit in the strain gauge there are lead ends or contact pads. On the object under study, strain gages are attached using a binder (glue). Deforming together with an elastic element, the strain gauge changes its electrical resistance in proportion to the strain (tension or compression) that occurs in the area of its attachment. For the measurement we use several strain gauges, which are connected to a bridge circuit.

According to the described principle, sensors with metal strain gauges function. There are also sensors with semiconductor strain gauges, piezoelectric force sensors, etc., which are used to solve specialized problems. Such sensors are expensive.

The advantages of strain gauges: high accuracy; exceptional adaptability in technical applications that provide the greatest range of application when measuring mechanical quantities; ease of processing the output signal and affordable price.

The fundamental point in the design of SGFS is the choice of the shape of the sensitive elastic element and the method of application of the load. Among the most commonly used forms of SGFS sensors membrane, column, console and S-type should be noted.
The main sensor element of the sensor is a membrane elastic element, made in the form of a bowl, which is placed between the support plates. On the inner surface of the elastic element, there are pasted strain gauges included in the measuring circuitry.

In the process of applying the load, the elastic element is deformed. Deformation in places of the sticker is transmitted to strain gauges that change their electrical resistance. The generated electrical signal enters the measuring circuit and is converted to the readings of the scale. An important parameter for processing the output signal is the sensitivity of the sensor, determined by the magnitude of the output signal at full load.

The current growth in requirements for primary transducers and measuring devices makes it important to solve the problem of improving the quality of an AEE not only in the process of their manufacture, but in their modeling and calculation. This led to the emergence of new computational and experimental methods, which led to a change in the overall design methodology for AEE.

Currently, there are a large number of different methods for calculating the AEE, but there is not a single simple and at the same time universal and effective method. In this regard, in the proposed project, the greatest attention is paid to the creation of alternative methods for calculating the sensitivity of an AEE, which could simultaneously rely on both analytical methods of classical mechanics, the theory of elasticity and resistance of materials, and numerical methods in order to use their advantages and compensate for their weaknesses.

The actual today is the development of modern contactless computerized methods for studying the elemental base of measuring equipment for determining stress-strain states. This is necessary to ensure reliable prediction of the quality of the element base of the measuring equipment during the performance of the functional control. The technique should be applicable also for the operational output control of the element base of the measuring equipment.

The development of computer-aided design (CAD), design and technological preparation of the production of an AEE is undoubtedly an urgent task, for the solution of which it is necessary to use both the numerical methods themselves and modern software systems based on them [7-11].

When solving the problems of creating CAD of the elastic element base of the AEE, it is necessary to carry out mathematical modeling of the deformation processes in a solid, and also to analyze the static and dynamic characteristics of their sensitive elements using the capabilities of modern software systems, for example, the ANSYS software package [2,8,12-14].

For this purpose, the finite element method (FEM) is most applicable, which makes it possible to automate the process of designing an elastic element base. The choice of the ANSYS software package is due to the wide range of FEM capabilities, which allows both simple linear stationary analysis and non-linear transient analysis.

2. Results
A typical calculation of an AEE in the software package includes three stages [9, 10, 15, 16]:

- creating a model of the final element;
- determination of boundary conditions;
- carrying out static and dynamic analysis.

As a result, a mathematical model of the physical prototype of AEE was created, which includes all nodes, elements, material properties, geometric characteristics, boundary conditions, and other objects. For this purpose, the ANSYS software package was used, which allows determining the geometry of the location of nodes and elements of a mathematical model. The created theoretical model of the ring-based design analyzer satisfies the following requirements [3]:

- a high degree of adequacy, which characterizes its static and dynamic parameters with satisfactory accuracy;
- low labor intensity with high performance;
- small time costs.

PC based on the following methods:

- generation of the geometric model itself;
• the creation of nodes and elements.

Due to limited resources, the work was carried out in a simplified GUI interface mode, based on the use of the software product COMPAS 3-D V15.

During the simulation, the model was split by a finite element mesh. The basic end element is the SOLID95 element with 20 nodes and 6 edges. It allows you to use the irregular form of the partitioning grid while not losing accuracy. The splitting was carried out into hexagonal elements with a maximum size not exceeding 2.5 mm [9,10,15,16].

When describing contact pairs of surfaces with nonlinearity taken into account, priority was given to the final elements CONTA174 and TARGE170. The CONTA174 element is applicable to simulate contact interaction (a three-dimensional contact element with 8 nodes), while the TARGE170 element is used to simulate a slip between three-dimensional response surfaces and a deformable surface. For the representation of contact pairs, the splitting was performed automatically.

In the analysis of transient, as well as in the conduct of harmonic and modal analysis, finite elements of the type MASS21 were used to simulate the loading process of the AEE. In this element, each direction of the coordinate system can be assigned its own values of masses and moments of inertia.

As the boundary conditions in the FEM, restrictions are imposed on the displacement of the ring-mounted AEE, the load, and the properties of materials. When using FEM, discrete equations of motion have the form:

\[ [M] \{\ddot{u}\} + [C] \{\dot{u}\} + [K] \{u\} = \{F\}, \quad (1) \]

where \{\dot{u}\} - the vector of nodal displacements for the whole body; \{\ddot{u}\}, \{\dot{u}\} - vectors of acceleration and velocity points of the body, [M], [C], [K] - “global” matrices of mass, damping and stiffness for the whole body, respectively;\{F\} – equivalent nodal force vector for the whole body [16].

In reality, ring cutters are attached to AEE due to the hole in the base, which imposes certain restrictions on the movement of its surface along three axes, therefore the complex of bases consists of only two guide bases and one stop. The loads in the static analysis were applied as a total force vector applied in the opposite direction along the axial axis. Whereas in dynamic analysis they were applied in the form of concentrated masses.

When calculating the statics, the result is the determination of the limit formation of the annular electric shock absorber, the optimal scheme of force transfer to it, the stress distribution fields and the most dangerous sections. The consideration of these factors allows optimizing the design of ring-mounted AEE [3].

In the course of the simulation, taking into account the constraints, variable loads were applied to the model, given by a tabular array that takes into account the dependence of the load on time.

When calculating the frequencies and forms of natural oscillations in the project, a modal analysis was used, assuming that the system is linear. Nonlinearity was not recorded. External forces and damping were reset.

Due to the geometric complexity of the model and a sufficiently frequent finite element mesh for the problems posed, it was decided to use the calculation by the block Lanczos method normalized by the mass matrix with an accuracy of six decimal places.

To assess the effect of the added mass on the natural frequencies, it is possible to carry out a modal analysis of a pre-stressed model.

As the boundary conditions in the FEM, restrictions are imposed on the displacement of the ring-mounted AEE, the load, and the properties of materials. When using FEM, discrete equations of motion have the form [5]:

\[ [M] \{\ddot{u}\} + [K] \{u\} = \{0\}. \quad (2) \]

If there is geometric complexity of the model and the high frequency of the finite element mesh, the block Lanczos method is used for the calculations.
The solutions obtained by modal analysis were refined using harmonic analysis and transient analysis, which are applicable only to linear models.

In a modal analysis of a pre-stressed model, the attached mass of the load is replaced by the load applied to the AEE, which corresponds to the weight of the load. This approach does not contradict the classical theory of oscillations.

Modal analysis makes it possible to save time on harmonic analysis and narrow the search range of natural frequencies.

Dynamic analysis requires disproportionately more time resources. As a result of dynamic analysis, it is possible to obtain frequency response and phase response, which allow us to estimate the stability [14]. The results of the dynamic calculation were compared with experimental data. For this purpose cyclograms of loading of an AEE were used.

3. Conclusion

Thus, the analysis of the static and dynamic characteristics of ring-mounted AEE and the simulation carried out using the FEM and a specialized software package allows you to successfully implement and use CAD-AEE measuring devices. The created mathematical model of an annular elastic sensing element has a high degree of adequacy, low labor intensity with high performance and low time costs. The results of the study are introduced into the practice of calculating and designing real structures, and are determined by applications for patents of the Russian Federation.

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