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FORMATION OF REFLECTIVE SHELLS BY ELECTRIC ARC SPRAYING AND APPLICATION OF COMPOSITE MATERIAL TO THE PUNCH

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Summary. *In the course of the work, the process of forming reflective shells and finding the position of grid elements after deformation was investigated. Fixation of mesh nodes by electric arc spraying. After that, a composite material such as polystyrene is applied to form reflective shells. Minimization of potential energy is carried out numerically by an iterative method. The result of the work is the formation of the antenna array shell by the method of electric arc spraying and the application of the composite material. The following forming operations of sheet metal stamping are known: drawing, rotary drawing, relief forming, trimming, including rubber and liquid drawing, hydromechanical drawing, explosion drawing, electric discharge stamping, electromagnetic stamping, hydropneumatic drawing, which allow to obtain a shell from sheet material (solid or gas and water permeable) by pressing it against a die or punch with a transfer medium.*
Key words: *electric arc spraying, mesh, composite material, punch, mirror, axisymmetric antenna.*

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Statement of the problem. The production of antenna systems and the manufacture of reflective surfaces is based on new technological and design ideas, the implementation of which requires appropriate scientific and technical support, and is possible in close cooperation between production and scientific potential. The technology of manufacturing mesh material shells can be used to produce axisymmetric and non-axisymmetric reflectors or individual elements of mirror antennas [1].

Analysis of known research results. The article deals with the methods of manufacturing antenna systems and reflective surfaces based on new technological and design ideas. The process of shell formation from mesh material is investigated. The complexity of describing the deformation process lies in the fact that the mesh behaves qualitatively differently when deformed than a sheet of solid material. This is due to its structure, in particular, the ability to rotate mutually perpendicular mesh wires relative to each other at the nodes. The design, production, and engineering were carried out by scientists from Ukraine and abroad, which is reflected in [2, 3].

Purpose of the work. The main design and technological ideas implemented in antenna systems are:

- preserving the basic principles of aviation technology in the production of antennas and excluding the influence of subjective factors on product quality;
- optimization of structures according to the criteria of stiffness, accuracy and weight;
- use without slipway assembly and on-site adjustment of antennas;
- use of vector diffraction methods in optimizing the electrodynamic characteristics of an antenna system at the design stage [4];
- the antenna positioning control system, control of its movement speed, diagnostics of its condition during operation, self-testing, is based on digital information processing [5].

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General provisions. Mirror (reflector) antennas are aperture antennas that use the phenomenon of wave reflection from a metal mirror (reflector) to convert weakly directed electromagnetic waves generated by a primary radiator (irradiator) into sharply directed waves emitted into space.

The most common types of mirrors are the paraboloid of rotation (Fig. 1) and the parabolic cylinder (Fig. 2).

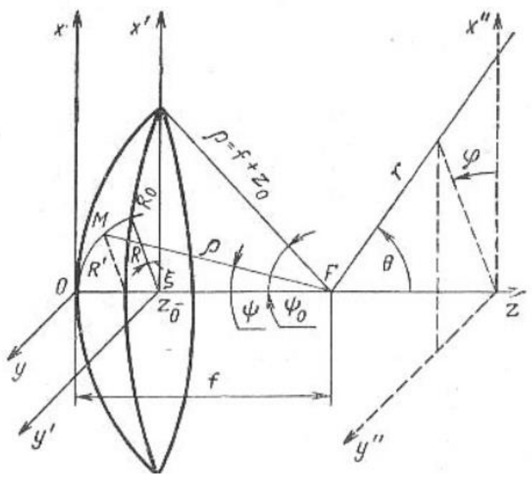

Figure 1. Paraboloid of rotation

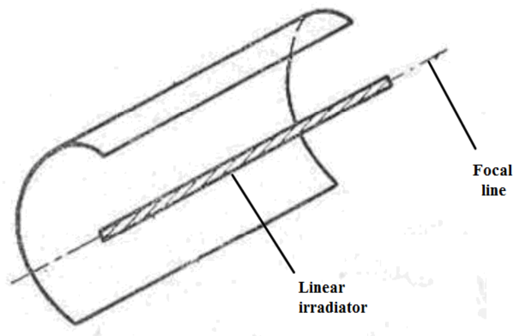

Figure 2. Parabolic cylinder

A paraboloid is a surface described by a parabola when it is rotated about its axis. A parabolic cylinder is formed by moving the parabola along parallel lines called the cylinder's generators. There are other mirrors based on a parabola.

The aperture of a mirror antenna is the part of the plane bounded by the outer edges of the reflector. The aperture of a parabolic cylinder has the shape of a rectangle along the sides a and b.

The focal length *f of a* parabolic reflector is the shortest distance from its surface to the point *F*, which is called the focus of the parabola.

The focal line of a parabolic cylinder is parallel to the cylinder's constituent parts and passes through the focus of the original parabola.

Mirror opening angle - $2\psi_0$ double the maximum angle value ψ

The equation of a parabola:

$$\rho = \frac{f}{\cos^2(0,5\psi)} \tag{1}$$

and the opening angle $2\psi_0$ is related to the diameter of the paraboloid d and its focal length f ratio:

$$ctg\psi_0 = \frac{4f}{d} \tag{2}$$

A reflector is called deep (short-focus) if: $2\psi_0 > \pi$, $f < 0,25d$ and the focus F is located in the middle of the mirror; if, $2\psi_0 < \pi$ $f > 0,25d$ and the focus is out of the plane of the opening, then the reflector is called shallow (long-focus). The phase center of the irradiator is aligned with the focus of the mirror, and a counterreflector is placed behind the irradiator to minimize the radiation of the irradiator outside the angle of the mirror opening.

The inner surface of the mirror should have the highest possible conductivity. To reduce the windage and weight of the mirror, it is sometimes made not of a solid surface but of a mesh or perforated sheets. The dimensions of the holes are selected so that no more than 1...2% of the power of the waves incident on the mirror leaks through them [6].

Existing methods of manufacturing reflective surfaces. Stamping**.** This process is widely known, so only some aspects are discussed. The practice of manufacturing shells for radar by stamping has determined the following.

Its advantages include:

- is a well-studied process both theoretically and practically;
- the existence of press equipment and tooling in Ukraine.

Disadvantages:

- The main disadvantage is the inability to obtain the exact geometry of the reflective surface of the RA with the reliability of repeating the process;
- when the overburden is more than 1.0 m, it is necessary to have special powerful pressing equipment and high losses on dies;
- shells for individual panel structures and non-axisymmetric RAs with a small depth of curved surface are produced from dies with very large deviations;
- large areas, powerful equipment, significant energy consumption, and highly qualified personnel are required both in the production process and during the release of products.

Therefore, stamping technology is not suitable for manufacturing high-precision shells.

Tightening. Borrowed from the aviation industry. It is mostly used to produce shells of individual panels or shell sectors with a thickness of 1.5–2.5 mm for prefabricated (riveted) RAs, which are assembled on special slipways with the installation and inspection of the working surface according to the «flag-template».

Advantages:

- the ability to manufacture symmetrical and asymmetrical shells in a wide range of sizes with the appropriate plasma support;
- the ability to manufacture symmetrical RAs from duralumin alloys that have significant hardness and stiffness during operation.

Disadvantages:

- manufacturing accuracy of parts is not higher than +0.6 mm;
- expensive, special powerful equipment that takes up large areas;

Such equipment exists only at Ukrainian aircraft plants.

Rotary run-in. Rotary turning (RR) is performed on lathes or lobing machines. The curved surface is programmed by a computer numerical control (CNC).

The tool is a hardened steel roller. Plastic deformation occurs at the point of contact between the roller and the workpiece.

There are two ways of RO:

- rolling on a rigid punch;
- free running without punching

On a rigid punch. The punch, most often made of a cast iron or steel casting, is mounted on a machine tool platen and, in most cases, immediately machined on the machine on a working surface that matches the shape and dimensions of the theoretical reflective surface of the RA. At the top, in the center of the punch, there is a pin for basing the workpiece, which is a circle with a small hole in the center.

The caliper with a running-in roller moves according to a predetermined program, in accordance with the punch surface from its center to the periphery. At the same time, the metal is plastically deformed on the punch in the contact zone due to the clamping force and a curved surface of the part is formed.

There is no control over the accuracy of the resulting shape, as it is believed that it is maintained by the punch.

Advantages:

- the shells are produced with a fairly high accuracy, deviations within +0.3 mm, and reliable process repeatability;
- the ability to obtain the required diameters and depths of the RA profile in a wide range, given the availability of appropriate equipment and punches;
- short production time.

This is the most efficient way to produce radar shells with a diameter of up to 1.5 m for wavelengths up to 10 mm. Larger diameter shells are also quite accurate, but during subsequent assembly of the radar, they partially distort the shape due to the action of the frame's force elements.

Disadvantages:

- the need for large carousel or CNC lathes when forming shells with a diameter of more than 0.9 m, and, as a result, high costs;
- Dependence of RA accuracy on the performance professionalism of the work shift;
- the need to have a separate machine for machining only one RA diameter, with a size of 1.5–2.5 m, due to the difficulty of removing and installing the punch (especially on lobing machines);
- obtaining only axisymmetric RAs for a frequency range not exceeding 10 mm due to the wave traces of the roller remaining on the reflecting surface.

Kramatorsk Heavy Machine Building Plant manufactures lobing machines with a processing diameter of up to 2.5 m. The process of rotary rolling on a rigid punch is well mastered at Ternopil-based Ternotechn, which produces shells from 0.4 to 2.5 m.

Free running (without punch). This is a very promising method. So far, it has been implemented only on carousel machines, although there is every opportunity to implement it on lobing machines. The essence of the process is as follows.

A fixture is mounted on the platen, which is a conventional stand for mounting and securing the workpiece. The workpiece in the form of a circle is mounted on the stand, which has an annular protrusion and hinged bolts. A ring with bolt slots and an annular groove is placed on top, which evenly seats the periphery of the workpiece, forming a flanging along the annular projection and holding it stationary. The die is rotated. The roller moves along the working (reflective) surface from the center to the periphery and in several (4–6) passes pushes the workpiece to form the shell profile.

The process of RO is carried out with the gradual stretching of more and more sections of the workpiece to the periphery. The shape accuracy is checked immediately on the fixture according to the template. During the molding process, it is also possible to check the accuracy of the shape.

Advantages:

- sufficiently high accuracy of the part shape within +0.4 mm on a diameter of 2.8 m;
- no need for a punch;
- the ability to produce different diameters and depths of shells with minimal tooling costs.

Disadvantages:

- the need for carousel machines, space for them, and maintenance;
- only axisymmetric shells are produced;
- the need for preliminary culling, significant time for fixing and processing;
- the presence of small waves on the surface from the roller marks, which makes it possible to use RA only in the frequency range not exceeding 10 mm.

Ukrainian enterprises have every opportunity to introduce this method of radioactive waste production.

Formation of the current working environment by pressure

The molding process is carried out by pressurizing a liquid or gas against a rigid die or punch. The simplicity and low cost of the equipment determine the increasing use of this method.

The process takes place without frictional forces at the deformation site and is accompanied by intense thinning of the workpiece deformed under biaxial tension. The maximum loads of the workpiece zones for different types of forming are not precisely determined, since theoretical premises differ from practical consequences.

Among the common methods of producing RA, static hydro- and gas-forming have found a special place.

The advantages of these methods include:

- simplicity and low cost of the process and equipment;
- there is no need for highly qualified personnel;
- good accuracy of +0.1 mm with reliable process repeatability;
- short process time;
- no mechanical damage to the working surface of the shell, which makes it possible to use it for radar in the millimeter range;
- the possibility of obtaining both axisymmetric and non-axisymmetric RAs;
- the ability to organize production in small areas and enterprises.

Disadvantages:

- limited depth of molding of the part, $h/d < 0.21$;
- the need to have a matrix for each type of RA;
- hydroforming, due to the high carelessness of the process, gives unsatisfactory working conditions (humidity, corrosion of equipment), and water drainage requires a sewer system;
- the appearance of an under-formed area at the top of the shell, which reduces the accuracy [7].

Formation of shells by electric arc spraying and application of composite material. This is because the formation of this material consists of several stages. The first stage is deformation of the two-dimensional mesh and fixing of the nodes by electric arc spraying with aluminum. The second stage, after sputtering on the punch, is to obtain a surface with a high temperature and apply a composite material such as polystyrene.

Polystyrene is a polymeric material that is used in the manufacture of various products due to its unique properties. Here's a closer look at the chemical properties of polystyrene:

- Thermoplasticity: Polystyrene is a thermoplastic material, which means it can easily melt at a certain temperature and be molded into different products. This makes it possible to produce polystyrene products in different shapes and sizes.
- Chemical resistance: polystyrene has a fairly high chemical resistance to many substances, including acids and alkalis, which makes it resistant to destruction in contact with them. However, it can react with some organic solvents, so this should be taken into account when choosing a material for a particular application.

- Electrical and thermal insulation: Polystyrene has low thermal conductivity and good electrical insulation, making it useful for the production of insulation materials, including thermal insulation panels for buildings and electrical insulators.
- Transparency: In its clear form, which is often used, polystyrene can be very transparent and transmit light better than glass. This makes it popular for the production of a variety of packaging materials and display cases.
- Mechanical strength: While some types of polystyrene can be brittle, there are also impact-resistant variations of this material that have increased strength and resistance to mechanical stress [8].

Since the first stage is the most important because a reflective surface is formed on the punch, the study of the shell formation process consists of predicting and verifying the deformation of a two-dimensional mesh. The difficulty of describing the deformation process is that the mesh behaves qualitatively differently when deformed than a sheet of solid material. This is due to its structure, in particular, the ability to rotate mutually perpendicular mesh wires relative to each other at the nodes. In addition, the conditions that the solution must satisfy differ from the standard ones: the surface on which the mesh should lie after deformation is specified, while the forces applied to the mesh at the nodes remain unknown in the problem formulation.

Finding the position of mesh elements after deformation is reduced to finding the position of mesh nodes after deformation. This problem must be solved with known displacement vectors of all nodes during deformation.

Therefore, the most general approach is used in solving the problem, namely the theorem of the minimum potential energy of the system in the equilibrium position. At the same time, friction in the system is neglected; it can be taken into account when improving the developed methodology. The minimization of the potential energy is carried out numerically by an iterative method.

The deformation depends on the forces applied to the ends of the mesh element. The stiffness matrix of the element is found using the DIP-FEA package, for which the element model is created and, given unit forces for each direction, the applied displacement load is calculated.

Mesh deformation process. This section is devoted to the development and verification of deformation of a two-dimensional mesh.

The complexity of describing the deformation process lies in the fact that the mesh behaves qualitatively differently during deformation than a sheet of solid material [9].

This is due to its structure, in particular, the ability to rotate mutually perpendicular mesh wires relative to each other at the nodes.

In addition, as described in more detail below, the conditions that the solution must satisfy differ from the standard ones: the surface on which the mesh should lie after deformation is specified, while the forces applied to the mesh at the nodes remain unknown when the problem is formulated.

Therefore, the most general approach was used to solve the problem, namely the theorem of the minimum potential energy of the system in the equilibrium position. At the same time, friction in the system, as usual, is neglected; it can be taken into account when improving the developed methodology.

The potential energy is minimized numerically by an iterative method. The problem statement, solution methods, and software implementation of the method are described below.

Problem statement. A surface of rotation is given, the equations of which are described by the following system:

$$\begin{cases} z=f(\rho), \\ \rho=\sqrt{x^2+y^2} \end{cases} \quad (3)$$

The surface is given in the cylindrical coordinate system. When ρ is greater than some value of R0, f(ρ)=0.

A grid that was undeformed in the plane z=0 and had a spacing of s is deformed so that it lies on a given surface.

The mold is formed using a ring with an axis radius equal to R0 (Fig. 3).

Friction in the system is completely neglected. The task is to find the position of the mesh elements after deformation.

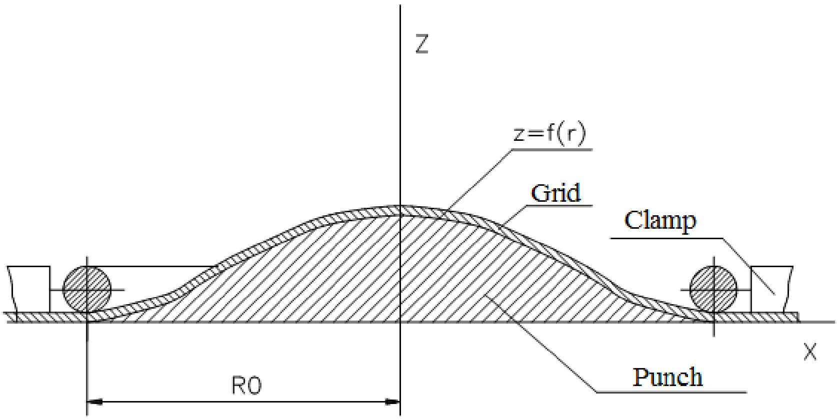

Figure 3. Scheme of grid formatio

Solution methodology**.** Before developing a solution methodology, it is necessary to clarify how the grid position should be set. The easiest way to do this is to reference the mesh nodes (i.e., the intersection points of mutually perpendicular mesh wires).

For this purpose, we assume that only rotations of the mesh wires relative to each other are allowed at the nodes, while displacements are not allowed. In fact, displacements (small ones) do exist, but they can be neglected to a first approximation. Thus, under the assumptions made, the position of the mesh will be fully known if the positions of its nodes are known. Therefore, the problem is reduced to finding the position of the mesh nodes after deformation [10].

Description of the grid position. When solving the problem due to symmetry, it is advisable to consider only the part of the grid that is in the first square. To find the position of the grid nodes as a whole, it is enough to consider that the grid has symmetry C_4 about the z-axis.

The node of the grid will be numbered with two numbers, i and j (Fig. 3). The problem will be solved if the displacement vectors of all nodes under deformation are found.

We denote the displacement vector of node (i,j) as u_{ij}. There are a finite number of such vectors. Along with the vectors u_{ij} , we also introduce the vector mapping function $u(x, y)$.

The meaning of this function is that at each point (x,y) of the plane z=0, the vector $u(x, y)$ is assigned to the vector (x, y) , and thus a mapping of the plane z=0 to the surface is given, each point of which is some point of the plane z=0 shifted by the vector $u(x, y)$. The mapping is assumed to be mutually unambiguous, and the function $u(x, y)$ is assumed to be continuously differentiable over the entire domain of definition. Let us impose another condition on the function $u(x, y)$: if x_j, y_i is the coordinates of the node (i,j), then it must be: $u(x_j y_i) = u_{ij}$.

In other words, let's define the function $u(x, y)$ so that it maps the grid to the surface.

Suppose that before the mesh was deformed, some of its wires were parallel to the x-axis, i.e., had the equation $y = y_0$.

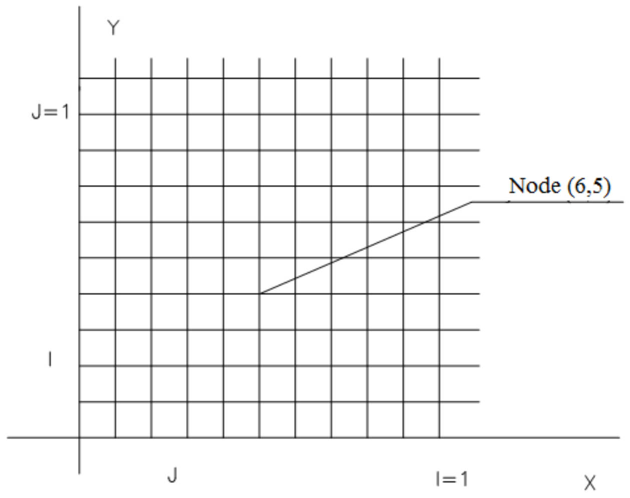

Figure 4. Node numbering scheme

Then, as it directly follows from the definition of the function $u(x, y)$, after deformation, the wire will lie on a curve whose equation in vector form is as follows:

$$\begin{cases} R(x) = R_x(x) \cdot i + R_y(x) \cdot j + R_z(x) \cdot k \\ R_x(x) = x + u_x(x, y_0) \\ R_y(x) = y + u_y(x, y_0) \\ R_z(x) = u_z(x, y_0) \end{cases} \tag{4}$$

where i,j,k are the coordinates of the x,y,z axes of the global coordinate system.

Given R(x), you can also find the tangent line to the wire at any point.

Energy of the grid. When calculating the energy of the grid, we use an obvious fact: the energy of the entire grid is equal to the sum of the energy of its parts. The smallest element of the grid is a part of a wire with a length of a period (Figure 5) [11].

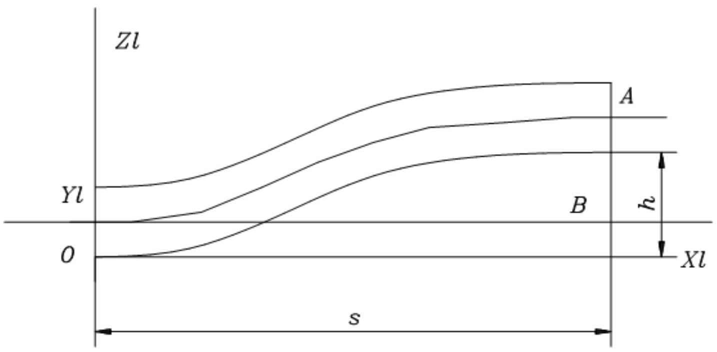

Figure 5. A grid element

The energy of the entire mesh can be found by calculating the energy of each element and adding the values for all elements. Obviously, the energy of an element depends only ondeformation of the element itself. The deformation, in turn, depends on the forces applied to the ends of the element.

Let's place the local coordinate system of the element as shown in Figure 5. In this case, point 0 (the left end of the rod) will be considered rigidly fixed.force P and a moment M are applied to the ends of the element Let's combine these two force factors into one six-dimensional vector F_i, with $F_{1,2,3} = P_{x,y,z}$ and $F_{4,5,6} = M_{x,y,z}$.

When you apply these forces, point A will move to some vector Δ and return to some vector φ.

The last two vectors will also be combined into one vector D_i, and there is a correspondence between $D_{1,2,3} = \Delta_{x,y,z}$ and $D_{4,5,6} = \varphi_{x,y,z}$.

In terms of Hooke's law, the relationship between the components F_i and D_i is linear. In its most general form, this relationship is expressed by the formula:

$$F_i = \sum_{j=1}^{6} C_{ij} \cdot D_j \tag{5}$$

where C_{ij} is a sixth-order square matrix, which we call the stiffness matrix.

The inverse matrix is called the malleability matrix:

$$B_{ij} = (C^{-1})_{ij} \tag{6}$$

Suppose we have an equilibrium state with some given forces F_i. Let's change these forces to dF_i. In this case, we will have an increase in displacements dD_i:

$$dD_i = \sum_{j=1}^{6} B_{ij} \cdot dF_j, \tag{7}$$

When the displacements change, the forces applied to the element at point A will do some work. According to the law of conservation of energy, this work is equal to the change in the potential energy of the element. Therefore, for the element's potential energy differential, we have the following expression [12]:

$$dU = \sum_{i=1}^{6} \cdot (\sum_{j=1}^{6} C_{ij} \cdot D_j) \cdot dD_i, \tag{8}$$

It is easy to see that dU is indeed a complete differential. This can be easily shown by using the order-reversal theorem, which states that for the function U, the variables D_i and Dj must be equal:

$$\frac{\partial^2 U}{\partial^2 D_i} \cdot \partial D_j = \frac{\partial^2 U}{\partial^2 D_j} \cdot \partial D_i \tag{9}$$

It is easy to see, using (8), that condition (9) can be rewritten as $C_{ij} = C_{ji}$. This means that the stiffness matrix must be symmetric. As practical calculations show, this is indeed the case. Therefore, dU is a complete differential. The function U itself can be found by simple integration and has the following form:

$$U = \frac{1}{2} \cdot \sum_{i=1}^{6} C_{ii} \cdot D_i^2 + \sum_{j>i} C_{ij} \cdot D_i \cdot D_j \tag{10}$$

According to the physical meaning of the function U as the potential strain energy of a mesh element, U should be positive definite. Specific numerical calculations have confirmed this for one case. For physical reasons, this should be true in general.

Finding the stiffness matrix of an element. The stiffness matrix of an element can be found using the DIP-MKE package. To do this, create a model of the element in the package according to Fig. 5. If the element is subjected to such forces in turn that in each case only one component in the vector F_i is different from 0 (alternately from the first to the sixth), and this component is equal to 1.

According to the relationship between displacements and forces for an element:

$$D_i = \sum_{j=1}^{6} B_{ij} \cdot F_j \tag{11}$$

B_{ij} is equal to D_i when a unit force is applied in the «direction» j. C_{ij} is then found as the inverse of B_{ij}.

Given unit forces for each direction of load application, the displacements are calculated by the package. Illustrations showing the deformations of the element when loads are applied are given in the graphical part of the paper.

The inverse matrix is found by a program written in Borland Pascal 7.0. For a mesh with a spacing of 7.5 mm made of steel wire with a diameter of 0.75 mm, the stiffness matrix is shown below. As expected, it turned out to be symmetrical (with an accuracy of errors caused by rounding).

Table 1

Stiffness matrix of a grid element

i/j	1	2	3	4	5	6
1	2.582E+05	9.566E-10	1.405E+06	7.845E-13	-4.415E+02	2.163E-14
2	9.612E-10	8.962E+04	5.333E-11	3.361E=02	2.061E-13	-3.361E+01
3	1.405E+0.6	1.318E-11	1.181E+07	-2.354E-13	-8.395E+02	-2.311E-15
4	8.073E-13	3.361E+02	-3.356E-14	1.694E+00	-3.566E-16	-1.346E-01
5	-4.415E+02	2.092E-13	-8.395E+02	-3.414E-16	1.7766E+00	-7.324E-17
6	1.891E-14	-3.361E+01	-2.328E-14	-1.346E-01	-7.048E-17	3.611E-01

Finding D_i for the element. Consider an element that is projected on the plane z=0 in a segment parallel to the x-axis in an undeformed state. Let this element be bounded by the nodes *(j,i)* and *(j+1,i)*.

The coordinates of the nodes in the undeformed state have the following values:

$$\begin{cases} x_0 = (j-1)\cdot s \\ y_0 = (i-1)\cdot s \\ x_B = j\cdot s \\ y_B = (i-1)\cdot s \end{cases} \tag{12}$$

In the deformed state, the coordinates of the nodes have values:

$$\begin{cases} x_0^i = x_0 + u_x(x_0, y_0) \\ y_0^i = y_0 + u_y(x_0, y_0) \\ z_0^i = u_z(x_0, y_0) \\ x_A^i = x_A + u_x(x_A, y_A) \\ y_A^i = y_A + u_y(x_A, y_A) \\ z_A^i = u_z(x_A, y_A) \end{cases} \tag{13}$$

The deformation vector D_i of an element must be expressed in the local coordinate system of the element (Figure 5). To do this, first of all, let's find the orthoi of the local coordinate system (or rather their coordinates in the global coordinate system). As can be seen from Figure 5, the ortho of the x_l axis coincides with the tangent to the element at point 0. Therefore, we have:

$$\begin{cases} i_l = \dfrac{l}{|l|} \\ l_x = 1 + \dfrac{\partial u_x}{\partial x} \\ l_y = \dfrac{\partial u_y}{\partial x} \\ l_z = \dfrac{\partial u_z}{\partial x} \end{cases}, \tag{14}$$

where the derivatives are taken at the point (x_0, y_0).

Next, we assume that the ortho of the z_l axis coincides with the normal to the surface (1) at point 0.

Then:

$$\begin{cases} k_l = \frac{l}{|l|} \\ l_x = -\frac{\partial z}{\partial x} = -\frac{x}{\rho} \cdot \frac{\partial z}{\partial \rho} \\ l_y = -\frac{\partial z}{\partial y} = -\frac{y}{\rho} \cdot \frac{\partial z}{\partial \rho} \\ l_z = 1 \end{cases} \quad (15)$$

Finally, the orth of the y_l axis is simply $j_l = \left[k_l, i_l\right]$, as it is in any right-handed coordinate system.

For an undeformed element, the coordinates of the end A would be:

$$R_A^0 = R_0 + i_l \cdot s + k_l \cdot h, \quad (16)$$

where R_0 is the radius vector of point 0

In fact, R_A looks like this:

$$R_A = R_B + k_l \cdot h, \quad (17)$$

where R_B is the radius vector of point D;

k_l – is the normal to the surface (1) at point B.

From (16) and (17), the displacement vector is equal:

$$\begin{cases} \Delta = R_A - R_A^0 \\ D_{1,2,3} = (\Delta \cdot (i_l, j_l, k_l)) \end{cases}, \quad (18)$$

For small end angles (in radians), the following relationships also apply:

$$\begin{cases} D_4 = \varphi_x = -\left|k_l^i - k_l\right| \cdot \mathrm{si}\,gn\left[(k_l^i - k_l) \cdot j_l\right] \\ D_5 = \phi_y = -l_{zl} \\ D_6 = \varphi_z = l_{Yl} \end{cases}, \quad (19)$$

where, l_{Zl} l_{Yl} are the components of a single vector tangent to the element at point A in the local coordinate system. They can be found by taking the derivatives at point B.

Thus, it was possible to express D_l in terms of *u(x,y)*. When implementing the method, the derivatives of *u(x,y)* should be (of course, approximately) expressed as u_{ij}. For example, for node *(i,j)* we have:

$$\frac{\partial u_x}{\partial y} \approx \frac{u_{i+1,j}^x - u_{i-1,j}^x}{2s}, \quad (20)$$

In this way, D_i is expressed through u_{ij}, which is necessary.

Minimize energy consumption. According to the method of solving the problem, energy minimization is planned to be carried out numerically as a minimization of a function of many variables. In this case, the energy depends on the variables u_{ij}.

First, we write down the zero approximation:

$$\begin{cases} u_{ij}^{x} = 0 \\ u_{ij}^{y} = 0 \\ u_{ij}^{z} = f(s\sqrt{(i-1)^2 + (j-1)^2}) \end{cases}, \tag{21}$$

Then, as described above, we find the energy of the mesh $E(u_{ij})$ and partially the derivatives of the displacements:

$$a_{ij}^{m} = \frac{\partial E}{\partial u_{ij}^{m}} \tag{21}$$

To reduce the energy, we take the following approximations u_{ij} in the form:

$$(u_{ij}^{m})_{k+1} = (u_{ij}^{m})_{k} - \lambda \cdot (u_{ij}^{m})_{k}, \tag{22}$$

where k is the approximation number;

λ – some became>0;

The energy change is expressed by the formula:

$$dE_k = \sum_{i,j,m} \frac{\partial E}{\partial u_{i,j}^{m}} du_{i,j}^{m} = -\lambda \sum_{i,j,m} (a_{i,j}^{m})_k^2, \tag{23}$$

As can be seen from (23), $dE_k \le 0$ and $dE_k = 0$ only if all derivatives of E are 0.

The value of λ should be chosen experimentally. By calculating the derivatives at some point in the space u_{ij}, you can improve the solution until E_k starts to grow. Then you should find the derivatives at a new point and continue the process. There is a way to find λ directly, but it requires the numerical calculation of the derivatives of E by u_{ij}. It is planned to be implemented in the future [13].

Implementation of the developed method.

The study of shell formation consists of predicting and verifying the deformation of a two-dimensional mesh.

The method was tested by manufacturing an axisymmetric antenna mirror with a diameter of 1.5 meters. A mesh made of galvanized steel wire with a diameter of 0.5 mm and a mesh size of 5 mm was used as a blank. The coating was carried out by an electric arc sprayer with aluminum wire on an industrial installation.

The described method of solving the problem is implemented for the case when f(p) is the following function (Fig. 6).

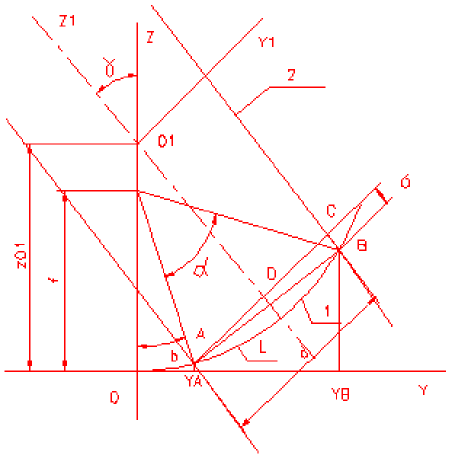

Figure 6. Focal length of an axisymmetric antenna mirror

Figure 7. Mirror of an axisymmetric antenna with a diameter of 1.5 meters

As can be seen from Fig. 5, R_0 =b+d. If the parabola has a focal length f, then as we can show mathematically, we get:

$$\begin{cases} d = r * \dfrac{b}{\sqrt{4f^2 + b^2}}, \\ a = \dfrac{b^2}{4f} + r * (1 - \dfrac{b}{\sqrt{4f^2 + b^2}}); \end{cases} \tag{24}$$

The following values of the variables in (24) are used in the solution:

r=12mm; b=200mm; f=500mm.

The mesh was taken in the form of a square with a mesh size of l=5 mm. The resulting shape of the sprayed mesh is shown in Fig. 7. The mirror of the axisymmetric antenna with a diameter of 1.5 meters was sputtered with an electric arc sprayer using aluminum wire on an industrial installation [14].

Conclusion. In the course of the work, the methods of manufacturing antenna systems and manufacturing reflective surfaces based on new technological and design ideas are considered. The process of formation of shells from mesh material that can be used for the manufacture of axisymmetric and non-axisymmetric reflectors or individual elements of mirror antennas is investigated.

One of the tasks investigated in shell formation is to find the position of mesh elements after deformation, which in our case is reduced to finding the position of mesh nodes after deformation. finding the position of mesh elements after deformation.

The potential energy is minimized numerically by an iterative method. The energy calculation uses the obvious fact that the energy of an element depends only on the deformation of the element itself, and the deformation, in turn, depends on the forces applied to the ends of the element. It is also obvious that the energy of the entire mesh is equal to the sum of the energies of its parts.

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УТВОРЕННЯ ВІДБИВАЮЧИХ ОБОЛОНОК МЕТОДОМ ЕЛЕКТРОДУГОВОГО НАПИЛЕННЯ ТА НАНЕСЕННЯМ КОМПОЗИЦІЙНОГО МАТЕРІАЛУ НА ПУАНСОН

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Резюме. *Досліджено процес утворення відбиваючих оболонок, знаходження положення елементів сітки після деформування. Фіксація вузлів сітки методом електродугового напилення. Опісля відбувається нанесення композиційного матеріалу типу полістирол для утворення відбиваючих оболонок. Мінімізацію потенціальної енергії здійснено чисельно ітераційним методом. Результатом роботи є утворення оболонки антенної решітки методом електродугового напилення та нанесення композиційного матеріалу. Досліджено процес утворення оболонок з сітчастого матеріалу, що може бути використано для виготовлення осесиметричних і неосесиметричних рефлекторів або окремих елементів дзеркальних* *антен. Однією з задач дослідження формування оболонки є знаходження положення елементів сітки після деформування, що у нашому випадку зводиться до знаходження положення вузлів сітки після деформації. Відомі формозмінюючі операції листового штампування: витяжка, ротаційна витяжка, рельєфне формування, обтяжка, в тому числі витяжка, рідиною, гідромеханічна витяжка, витяжка вибухом, штампування електричним розрядом, електромагнітне штампування, гідропневмовитяжка, які дозволяють отримати оболонку з листового матеріалу (суцільного чи газо- і гідропроникного) шляхом притискання його до матриці або пуансона передаючим середовищем.*

Основними конструкторсько-технологічними ідеями, які реалізуються в антенних системах, є:

- *збереження при виробництві антен основних принципів авіаційних технологій і з виключенням технологічних процесів впливу суб'єктивних факторів на якість продукції;*
- *оптимізація конструкцій за критеріями – жорсткість-точність-маса;*
- *використання без стапельного складання і юстування антен на об'єктах;*
- *використання методів векторної дифракції при оптимізації електродинамічних характеристик антенної системи на стадії проектування;*
- *система управління позиціювання антени, управління швидкостями її переміщення, діагностика стану при експлуатації, самотестування, що здійснюється на базі цифрового опрацювання інформації.*

Ключові слова: *електродугове напилення, сітка, композиційний матеріал, пуансон, дзеркало, осесиметрична антена.*

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