DEVELOPMENT OF HYDRO-CENTRIFUGAL METHOD OF FORMING WOMENS HEADWEAR

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Abstract: *The article is devoted to the development of a new hydro-centrifugal method of forming the heads of women's headwear from fabrics of suit and coat assortment. As a working environment, it is proposed to use a liquid-active working environment (LAWE) for the formation of complex spatial forms. Theoretical substantiation of the formation method is performed by developing a physical model of the process. A method, technique and equipment for hydro-centrifugal formation of women's headwear have been developed. The research of the method by conducting one-factor and multifactor experiments was performed and the optimal parameters of formation were established. The influence of main input factors on the quality of formation of headwear parts was investigated. The adequate mathematical models of the second order of formation process were obtained. The rational parameters of the hydro-centrifugal forming process, in which the best quality of formation is achieved, were identified for each fabric.*

Keywords: *hydro-centrifugal forming method, LAWE, women's hats, formation, methods of formation, coefficient of form stability, women's headwear.*

1   INTRODUCTION

During the existence of mankind, fashionable costume has undergone many transformations. A large number of inspirations for the costume [1, 2] created a multifaceted palette of shapes of various items of clothing. This is especially true for a women's clothing. Modern fashion is characterized by variety forms of women's hats. The most difficult in the technology of forming garments is the way to obtain a three-dimensional shape that approaches the surface of hemisphere. The complexity is due primarily to the anisotropy of properties of the fabrics, which is manifested in different stresses of material at the base, weft and at an angle to them in the deformation process [3]. The final shape of the part, obtained in the forming process, can be different from the shape of the forming element. Recently, in the field of formation, scientists are working in the development of a new ways, which take into account the deformation properties of textile materials in order to ensure a given shape. Formation of clothes details can occur according to application of classical and non-traditional methods of humid-thermal treatment (HTT) [4]. The classic methods of formation are: with the use of irons, presses and steam-air mannequins (formation

in the field of static loads). But they have a number of disadvantages [5]: different pressure of pillow surfaces on a different parts of textile materials; low mobility of the rough structure of textile materials; mismatch of the forms of a top and bottom pillow; impossibility of using a different pillow for the manufacture of products; small change of angles between systems of threads; deterioration of the quality of formation and increase in energy consumption due to the use of a small number of forming surfaces. Given these shortcomings of the classical methods of forming, it is justified to search for non-traditional, alternative, technologies for the formation of garments and hats (formation in the field of dynamic effort). The development of methods for forming parts of three-dimensional garments is accompanied by the search for ways to improve the forming process, from which we can identify four main areas [6-8]:

1. change of a number of forming surfaces and their location;
2. search for an alternative (rational) nature of the forming effort;
3. search the ways of force on the fabric without contact with the working bodies of the equipment;
4. search of an effect of firming force on the external and internal surface of the fabric.

In this case, the deformation of the textile material can be performed in different working environments and when using different in nature loads - forming methods.

In the works [4, 5, 8-13] the author's found that the dynamic methods of formation require attention in the study of the process of forming parts of garments and hats. They allow to a more efficient transformation of a flat textile material into a three-dimensional part by increasing the mobility of rough structure of the fabric. Also - changes occurring at the level of fine structure.

Among the known technical solutions should be noted the use of the centrifugal method of HTT garments [14-17]. It allows you to get rid of metal-cushions, reduce total costs compared to the press and increase productivity by 90%. It should be noted that in this method of forming the working environment is a pair in combination with a microwave, and also use one forming element.

The membrane method of a forming garment details is also original [18-21]. The peculiarity of this method is that the desired shape of the part is provided when using a heat-resistant elastic membrane. It is located under a rigid heating surface, which receives air of constant or pulsating pressure. In this case, the elastic shell, which is filled with air, provides a uniform force load on the material and increases contact with the forming surface. The greatest treatment effect is achieved in 25-30 cycles at loads of 0.02 MPa less than in static forming methods. The disadvantage of the membrane method of forming of garments should be considered the lack of interaction of the working environment, with the being processed fabric, as well as the unilateral action of the force load.

There is also a new technology of vibro-treatment using the energy of electromagnetic waves [22-25]. This forming method is based on the using a pulsating electromagnet field, created by the interaction of two spiral flexible coils: lower and upper. There are some disadvantages of such method: the presence of two forming elements; increased energy consumption of the method; humidification is performed using a spray, which effects on the forming quality. A method of forming, using dynamic load forces is also effective [23, 24, 26]. This technology is based on two ways of interaction of forming organs and parts of a clothing: vibrating and vibrating-impact.

According to the work data [27] dynamic methods of exposure on polymeric materials reduce the coefficient of friction between the fibers and threads of the fabric. This has a positive effect on the reconstruction of the rough structure of the material in the process of three-dimensional formation and provides the conditions for obtaining the spatial shape of the parts at low loads ($p = 3...9 \cdot 10^3$ Pa).

Analysis [28] showed, that in order to successfully solve the problem of improving the quality of garments, reducing labor intensity and saving energy resources, it is necessary to develop a new special equipment and improve technological processes of HTT, based on the development of new ways of forming, finding a new working environments, etc.

Depending of the method of impact of forming load on material there are following types of forming: pneumatic, hydraulic, mechanical and combined. Modern technologies of the forming three-dimensional products from flat blanks provide a combination of different ways for creating the forming load [10]. The penetration of water into the fibers leads to decrease of the forces of internal interaction between the chains of molecules and, accordingly, to a decrease of the resistance of textile materials to forming forces [9]. In addition, it is advisable to use water as a plasticizer, because plasticization occurs without destroying the supramolecular structure of the material. There is a partial swelling of the material, which leads to a change in the diameter of the fibers [29].

Analysis of the formation methods [30-34], in which is used LAWE as a working environment, showed the features of solving a number of disadvantages of classical formation methods:

- there is no need for the second forming element – it's functions are performed by LAWE;
- lack of temperature action as the main factor of classical technology;
- the forming force is transmitted to the deformable fabric directly by the working environment, and not by the working elements of the equipment.

The existence of such methods of the formation of garment parts and three-dimensional parts of hats proves the feasibility of studying LAWE and finding ways to optimize its properties.

At the same time, scientists don't pay enough attention to the development of various methods of headwear forming. Existing works [35-40] describe only certain aspects of objective task that considered in the work. Therefore, there is a need for a study of aspects of hats formation more thoroughly.

Recently, scientists are interested by the method, which use centrifugal forces. This method in combination with the new LAWE working environment can be the basis for the development of energy-saving and low-operating technology, which will perform high-quality forming operations. Therefore, the development of a hydro-centrifugal method of forming the women's headwear is an actual question.

2 EXPERIMENTAL

2.1 Physical model of hydro-centrifugal method of headwear forming

The study of the proposed method of formation should be based on the actual reflection of the studied phenomena. For this a physical model was used, which allowed to study the influence of individual parameters on physical processes. The process of forming parts in LAWE is very complex, is continuous and fills the space in the working chamber and the structure of the material without voids and gaps. Due to its fluidity, it has forces evenly distributed over the volume [10]. Any volume of liquid can arbitrarily change its shape under the action of any small forces.

Peculiarities of the force field formation and the nature of its distribution on the forming element taking into account the fabric structure were investigated in [14, 41]. The obtained models illustrate the physical essence of the action on fabric of the phenomenon of centrifugal force in the process of formation. The development of a physical model of the process of centrifugal formation in LAWE is to analyze the action of forming forces applied to the fabric, taking into account the surface characteristics of the forming element. Therefore, it is necessary to determine the model of behavior of systems of fabric threads as well as the nature of the distribution of forming forces on the surface of the headgear during a centrifugal forming.

When rotating a cylindrical drum around the vertical axis of the OY with an angular velocity ω there is a centrifugal force F_B (1). It operates on each elementary section of the textile material δS of the part, which is located on the formation element and fixed to the wall. The centrifugal force *Fb(H)* is determined by the formula [42]:

$$F_B = m(1).\omega^2.R \qquad (1)$$

where: *m(1)* - the mass of a single elementary section of textile material part, taking into account the moisture content [g/m²]; ω^2 - angular velocity of the shaft, rotating the drum, on which the forming element and the part are fixed [rad/s]; *R* - smallest distance from the axis of rotation to a given elementary section of the material [m].

Since the working environment of the forming is LAWE, therefore it is necessary to determine the mass of a single elementary part of the material, taking into account the moisture content by the formula:

$$m(1) = M_s.w \qquad (2)$$

where: M_s – surface density of textile material [g/m²]; *w* - coefficient that takes into account the moisture content of the molded part.

The moisture content *w* of the textile material is determined by the formula:

$$w = \frac{m_B - m_C}{m_C}.100 \qquad (3)$$

where: m_B - the mass of the part immediately after formation [g]; m_C - the mass of a completely dry part [g].

It is also necessary to take into account the angular velocity of the shaft with uniform rotation, which is as follows [42]:

$$\omega = 2\pi.n \qquad (4)$$

where: *n* - rotation frequency (number of revolutions per 1 second) [s⁻¹].

Substituting in the formula (1) expression (4), where find:

$$F_B = 4m_{(1)}.\pi n^2.R \qquad (5)$$

Consider the action of forming forces, namely the centrifugal force, as well as the interaction of the warp and weft threads of the textile material between themselves and the forming surface [14]. Based on the system of action of the deforming force F_V in the area of the warp thread, it is possible to determine the normal F_V^N and tangential F_V^T components:

$$F_V^N = F_V.\cos\varphi \qquad (6)$$

$$F_V^T = F_V.\sin\varphi \qquad (7)$$

The normal component of the centrifugal force F_V^N provides partial deformation of threads on thickness, without changing a network corner. In contrast to the normal tangential component F_V^T causes a shift of the main threads, resulting in a change in the magnitude of the network angle between the threads of the warp and weft. The magnitude of the shear deformation Δ*l* largely depends on: the tangential component of the centrifugal force; the frictional properties; the physical and mechanical properties of the textile material. The change in the fabric thickness and especially its pile structure depends on the normal component, as well as the elastic properties of the elements of the textile material.

Due to the fact, that the surface of the forming element has a hemispherical shape, respectively, each elementary section δ_S of the textile material is at different distances *R* from the axis of rotation. Therefore, the magnitudes of the forming forces vary over the entire surface of the material. The smallest centrifugal force will be concentrated on the least convex part of the forming element, and the largest - at its base. Since the drum contains a liquid (LAWE), it is necessary to investigate the nature of its action on the forminf process. As the drum rotates at a certain frequency, the liquid (LAWE) in it will gradually gain the same angular velocity ω as the drum, and its free surface will change [43-45]. In the central part the level of RARS will decrease, and at walls - will increase and all free surface will become some surface of rotation (Figure 1).
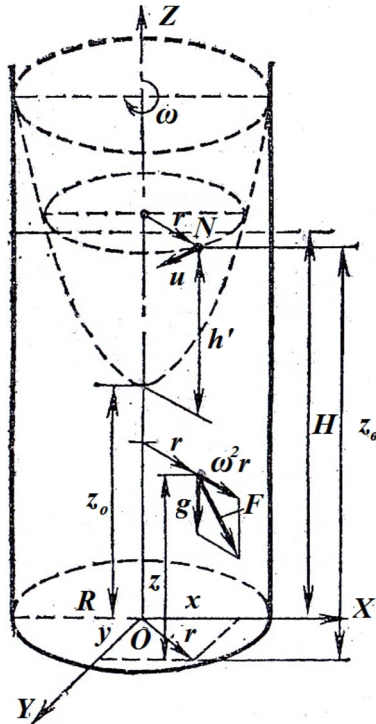
Figure 1 Determination of the free surface of a liquid rotating in an open cylindrical container: $OXYZ$ -coordinate system in which the cylindrical container is placed; R – the radius of the cylindrical tank; ω - the angular velocity of rotation; H - fluid level at rest; z_0 - the vertex of a free surface of liquid; z_v - coordinate of a free surface of the liquid; N - an arbitrary point on a free surface

When considering the motion of a liquid, it is broken down as solids into individual small elements [46-48]. To describe the motion of a liquid, we select an arbitrary liquid volume T, limited by the surface S. Write for him an expressing equation - the law of movement quantity: the time derivative of amount of system motion is equal to the sum of external forces, acting on it. This equation is an integral form of the fluid motion equation. Using the formulas of vector analysis, we obtain the differential form of the fluid motion equation:

$$\rho\overline{F} + \frac{\partial \overline{p}_x}{\partial x} + \frac{\partial \overline{p}_y}{\partial y} + \frac{\partial \overline{p}_z}{\partial z} = \rho\frac{d\overline{u}}{dt} \tag{8}$$

This equation is a vector form of the equation of motion of a fluid in stresses, which is equivalent to three equations in the projections on the coordinate axes x, y, z, having the form:

$$\begin{aligned} F_x + \frac{1}{\rho}\left(\frac{\partial p_{xx}}{\partial x} + \frac{\partial p_{yx}}{\partial y} + \frac{\partial p_{zx}}{\partial z} \right) &= \frac{du_x}{dt}; \\ F_y + \frac{1}{\rho}\left(\frac{\partial p_{xy}}{\partial x} + \frac{\partial p_{yy}}{\partial y} + \frac{\partial p_{zy}}{\partial z} \right) &= \frac{du_y}{dt}; \\ F_z + \frac{1}{\rho}\left(\frac{\partial p_{xz}}{\partial x} + \frac{\partial p_{yz}}{\partial y} + \frac{\partial p_{zz}}{\partial z} \right) &= \frac{du_z}{dt}. \end{aligned} \tag{9}$$

The height at which the point of free surface of liquid (arbitrary point N) is raised above the vertex of paraboloid is equal to:

$$h' = z_B - z_0\frac{\omega^2 r^2}{2g} \tag{10}$$

Ordinate z_0 the vertex of paraboloid of free surface at a given angular velocity depends on volume of liquid in the tank. If before the rotation of a tank the liquid level was horizontal and set at a height H, then the volume of liquid was equal to $\pi R^2 H$. As the drum rotates, a free surface becomes parabolic, the shape of liquid volume changes, and its value at density ρ=const remains unchanged:

$$\int_0^R (z_0 + \frac{\omega^2 r^2}{2g})2\pi r dr = \pi R^2 H \tag{11}$$

After integration, get:

$$H = z_0 + \frac{\omega^2 R^2}{4g} \tag{12}$$

Or

$$z_0 = H - \frac{\omega^2 R^2}{4g} \tag{13}$$

Assuming that z_0=0, then it is possible to find the angular velocity ω, in which a free surface of the liquid will touch the bottom of drum:

$$\omega = 2\frac{\sqrt{gH}}{R} \tag{14}$$

Substitute the obtained data into the equation of equilibrium of incompressible fluid with density ρ, which is a consequence of transformations of the equations of motion of Euler fluid:

$$d_p = \rho(Xdx + Ydy + Zdz) \tag{15}$$

where p – hydrostatic pressure.

$$dp = \frac{\partial p}{\partial x}dx + \frac{\partial p}{\partial y}dy + \frac{\partial p}{\partial z}dz$$

Then get:

$$d_p = \rho(\omega^2 xdx + \omega^2 ydy - gdz) \tag{16}$$

After integrating equation (15) obtain:

$$p = \rho(\frac{1}{2}\omega^2 r^2 - gz) + C_1 \tag{17}$$

Performing mathematical transformations and substituting a found value C_1 in (16), obtain:

$$p = p_{am} + \rho g(z_0 - z) + \frac{\omega^2 r^2}{2g} \tag{18}$$

Knowing that $h' = \frac{\omega^2 r^2}{2g}$ for any point it is possible to use the obtained results and write in the form:

$$p = p_{am} + \rho g\rho(z_0 - z + h')$$

or

$$p = p_{am} + \rho g h_s \tag{19}$$

where h_s – depth of immersion of a point under a free surface or a distance, measured vertically from a parabolic surface to the point under consideration.

Thus, in a liquid that is in a cylindrical container, the rotating pressure is distributed vertically by the hydrostatic law. According to Pascal's law, the value is the same for all points of fluid volume. So, given the property of hydrostatic pressure, it can be affirming, that the pressure applied to a free surface of the liquid is transmitted to all points of this liquid in all directions equally.

If limit the top of the open cylindrical container with a lid, with increasing angular velocity, the liquid near the side walls will begin to rest on its upper part, creating a hydrostatic pressure (Figure 2). In this case, the above law of pressure distribution is also valid.
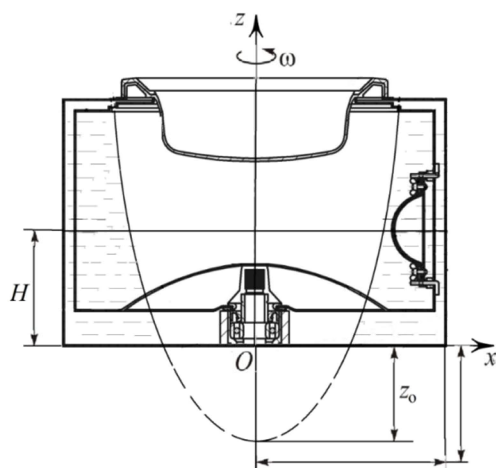

Figure 2 Determination of free surface of fluid rotating in a closed and cylindrical cavity: *OYZ* - coordinate system, in which the cylindrical capacity is placed; *R* - radius of cylindrical capacity; *ω* - angular velocity of rotation; *H* - fluid level at rest; *z₀* - the top of free surface of the liquid

Therefore, the physical essence of the improved centrifugal forming method using LAWE as a working environment is in action on the textile material, which is fixed on the forming element by centrifugal forces and circular flows of LAWE, which moisten the material and create additional forming force in the form of hydrostatic pressure.

2.2 Materials

A quality of forming operations primarily depends on the properties of material from which the garment is made. For manufacture of hats use different textile materials that differ in structure, fibrous composition, physical, mechanical and operational properties. There are: coat, suit fabrics, knitted fabrics, artificial and natural leather, suede and fur, velour, felt, duplicated materials, cotton, linen and silk fabrics.

One of the main properties that effect on forming process is a forming ability of the textile material, scratchiness and stiffness. They must be taken into account when choosing materials for headwear manufacture. A material and its structure significantly influence on forming ability.

The characteristics of the structure of textile materials on which the forming ability depends are:
- fibrous composition;
- thickness;
- density of material by warp and weft (number of main threads or weft threads located per 100 mm of length or width);
- linear density;
- surface density;
- linear filling (characterizes the density of fabric as a percentage of the maximum possible taking into account the thickness of threads and shows, what part of the fabric area is filled with parallel threads of the warp and weft);
- surface filling (indicates which part of the fabric is filled with threads of a two systems, taking into account the overlap of threads on each other when weaving);
- volumetric filling (shows what part of the volume of fabric is the volume of warp and weft threads);
- three-dimensional mass (shows the weight per unit volume of fabric);
- filling by weight;
- total porosity (characterized by the volume of fabric that is not filled with fiber);
- binding.

Structural characteristics in a complex determine the structure of fabric and effect on its physical and mechanical properties: strength, elongation, rigidity, drapeability, immutability, hygroscopicity, change of linear dimensions at HHT, ability to form, etc. The formation of textile materials is possible due to the fact, that they occupy a significant volume of air (the surface density of most fabrics doesn't exceed 500 g/m², porosity is close to 50-80%), and also the presence of mobile and stable connections in a structure of the textile material. With a decrease in the density of textile material, but with the same thickness of threads and weave, with a decrease in the number of threads by 10 cm, the fabric becomes more mobile.

For the formation of textile materials using LAWE as a working environment, it is proposed to use medium-density fabrics of linen, satin, satin or twill weaves with long overlaps, from hardware yarn, containing natural (preferably woollen) and chemical fibers. To study the centrifugal method of formation in LAWE, three fabrics of suit and coat range were selected, which are presented on the modern market and are in demand among consumers. These fabrics are used to make hats that can be combined with other garments (suits, coats), and thus create a complete ensemble. Selected textile materials are different in weave, fibrous composition, linear and surface density, thickness, etc. This will make it possible to investigate the proposed method of formatting for different fabrics, as well as to choose the optimal parameters of the forming process.

2.3 Experimental equipment

To implement an improved a centrifugal method of forming the textile materials, due to the use LAWE as a working environment, was developed experimental equipment, the scheme of which is presented on Figure 3.
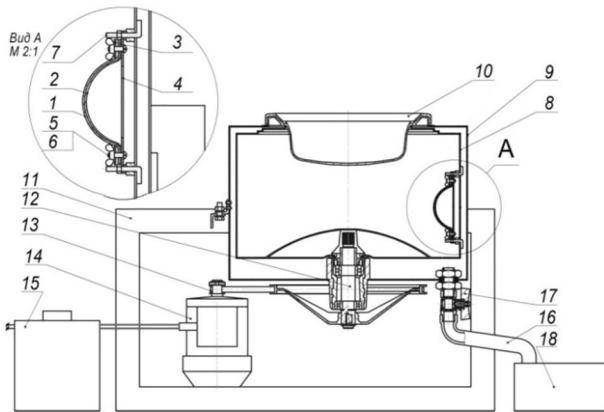

Figure 3 The scheme of experimental equipment for formation of the textile materials by hydro-centrifugal method: 1 - textile material; 2 - forming element; 3 - clamping ring; 4 - fastening platform; 5 - nut; 6 - screw; 7 - bolt; 8 - drum; 9 - forming chamber; 10 - camera cover; 11 - installation frame; 12 - shaft; 13 - belt drive; 14 - electric motor; 15 - laboratory transformer, 16 - valve; 17 - pipeline; 18 - tank

The main characteristics of developed experimental equipment are presented in the Table 1.

Table 1 Main characteristics of the experimental equipment

Characteristic	Specifications
Number of formation elements	3 psc
The height of the formation element	39 mm
The mass of one formation element	38.5 g
Drum speed	0...14 s^{-1}
LAWE volume	12...20 l
Laboratory autotransformer	RNO-250-2
Electric motor	INDESCO 1000 A
Overall dimensions of the drum diameter and height	470 mm 260 mm

Developed equipment provides a qualitative formation of headwear hats in LAWE. According to the active action of such environment provides effect on the fabric structure in the drum under pressure. This allows to form a stable shape of the hat in a relatively short period of the time, compared to the classic methods of hats forming. Developed equipment is presented on Figure 4 and shape fixation mechanism on Figure 5.
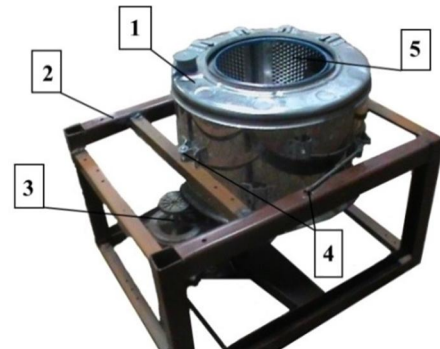

Figure 4 External view of developed experimental equipment of hydro-centrifugal method of headwear forming: 1 - forming chamber; 2 - installation frame; 3 - electric motor; 4 - drum fastening to the equipment; 5 - drum
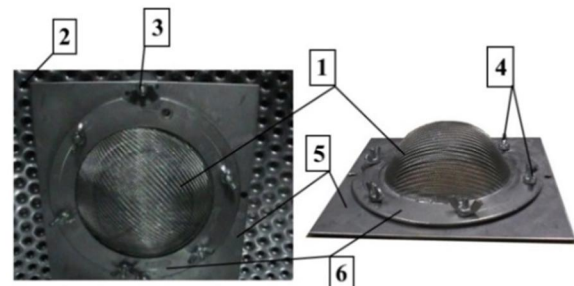

Figure 5 External view of form fixation element: 1 - forming element; 2 - drum; 3 - fixation of fastening platform; 4 - nut with screw; 5 - fastening platform; 6 - clamping ring

The fabrics used in the studies have their own characteristics (Table 2). The essence of the proposed method of formation on developed equipment is to action on the textile material by centrifugal forces and circular flows of LAWE, which moisten the material and create additional forming force.

Table 2 Physical and mechanical characteristics of fabrics

Characteristic	Fabrics type			
	Costume fabric №1	Costume fabric №2	Coat fabric №1	Coat fabric №2
Fibrous composition	100% wool	100% wool	78% wool 22% polyester	78% wool 22% polyester
Surface density M_s [g/m^2]	214	263	315	345
Number of threads per 10 cm, warp P_{wp}	158	229	138	154
Number of threads per 10 cm, weft P_{wf}	131	194	126	130
Binding type	twill 2/2	twill 2/2	twill 1/2	twill 2/2
Linear density of warp threads T_{wp} [tex]	75	25x2	100	120
Linear density of weft threads T_{wf} [tex]	75	54	102	124

2.4 Research method

Investigated method and equipment for forming parts of garments from textile materials under the action of a centrifugal force field and LAWE includes placing a sample of material on the forming element, fixing in the chamber for forming, wetting, and formation. Sampling of materials for forming and their cutting is performed from a roll or piece of fabric across its width with observance of parallelism of threads at cutting. Experimental investigations were performed using the method of small samples with a diameter of $d = 170$ mm. At least 3 tests are required to conduct experimental studies with an average guarantee error of 3% and a confidence level of 0.95.

The flat spot sample of textile material is fixed on a perforated forming element and a platform for fastening by means of a clamping ring. The platform with the forming element and the material is placed in the forming chamber on the bolts, fixed on the perforated wall of the drum. Then the chamber is filled with a certain volume of LAWE ($t = 18\text{-}20°C$) and closed with a lid. Through the laboratory autotransformer a voltage is applied to the AC motor, which provides rotational movements of the drum through the belt drive. The drum and forming elements rotate with a certain frequency, which is set by the regulator on the previously set scale of speeds, located on the transformer. The formation of the textile material takes place within the set time due to the action of centrifugal force and circular flows of LAWE, which moisten the material and create additional forming force.

3 RESULTS AND DISCUSSION

To verify the theoretical provisions set forth in the physical model of the process, a comprehensive experimental study was performed in terms of the choice of input parameters, their range, and their combined effect on the quality of the process.

In the work [14] to study the centrifugal method of forming a working environment which was a steam, the main input controlled parameters were the speed of drum rotation and steam pressure. A drum speed, vapor pressure and steaming time were used as input factors influencing on the centrifugal forming process.

For a preliminary study of the hydrocentric method of textile formation in LAWE on the experimental equipment, the input controlled factors were chosen: drum speed $n(x_1)$, LAWE volume $V(x_2)$ and forming time $t(x_3)$. The initial function and the criterion for optimizing this forming process is the coefficient of form stability K. Determining the influence of each of the factors separately on the process of centrifugal formation and their quantitative indicators was carried out in the framework of one-factor experiments. Levels and intervals of parameters variation that effect on the hydrocentric method of formation in LAWE are selected on the basis of literature sources [14], as well as based on the physical capabilities of this experimental setup are shown in Table 3.

Table 3 Levels and intervals of factors variation of influencing the process of centrifugal formation

Levels of variation	Parameters of the forming process		
	Frequency rotation n [s^{-1}] x_1	LAWE volume V [l] x_2	Formation time t [s] x_3
+2	14	20	180
+1	12	18	150
0	10	16	120
−1	8	14	90
−2	6	12	60
Interval of variation	2	2	30

Similar studies of the hydrocentric forming method were conducted for the three fabrics of suit and a three coat assortments, selected in the previous section. In the experimental study of coat fabrics, the regression equations of the dependences between selected input parameters and a coefficient of form stability K were obtained. This is done as a result of analysis of the influence of each factors separately on the process of centrifugal method of forming the parts from textile materials. They adequately characterize the studied process, which is confirmed by the reliability of the approximation. Regression dependencies $K = f(x_i)$ between the rotational speed, the volume of LAWE, the time of formation and a coefficient of shape stability, are described by polynomials of the third degree and are presented in the Table 4.

Table 4 Regression dependencies $K = f(n)$, $K = f(V)$ and $K = f(t)$ in the study of coat fabrics

Process factors	Regression equation	Reliability of approximation
Rotation speed [s^{-1}]	$K = 0.89 \cdot 10^{-3} n^3 - 0.02774 n^2 + 0.26508 n - 0.6974$	$R^2 = 0.99$
LAWE volume [l]	$K = 0.13 \cdot 10^{-3} V^3 - 0.00618 V^2 + 0.08509 V - 0.25989$	$R^2 = 0.98$
Formation time [s]	$K = -0.004 \cdot 10^{6} t^3 + 0.003 \cdot 10^{-3} t^2 - 0.29 \cdot 10^{3} t + 0.0726$	$R^2 = 0.98$

Graphical dependences of the coefficient of form stability on main parameters of the process in the study of centrifugal forming method parts of hats from coat fabrics are presented in Figures 6-8.
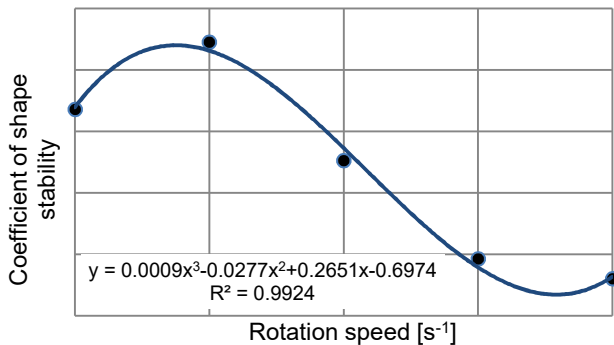

Figure 6 Dependence of the coefficient of stability on the rotation speed in the study of coat fabrics
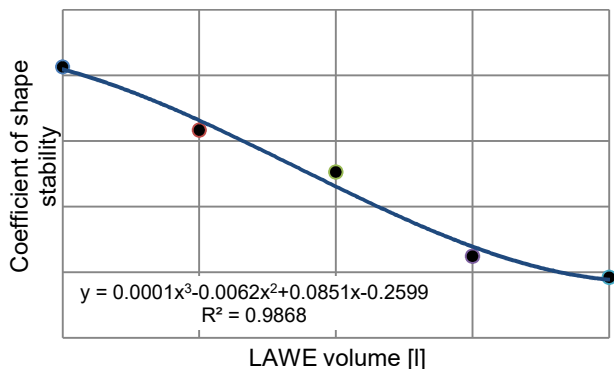
$y = 0.0009x^3 - 0.0277x^2 + 0.2651x - 0.6974$
$R^2 = 0.9924$

Figure 7 Dependence of the coefficient of stability on the volume of LAWE in the study of coat fabrics
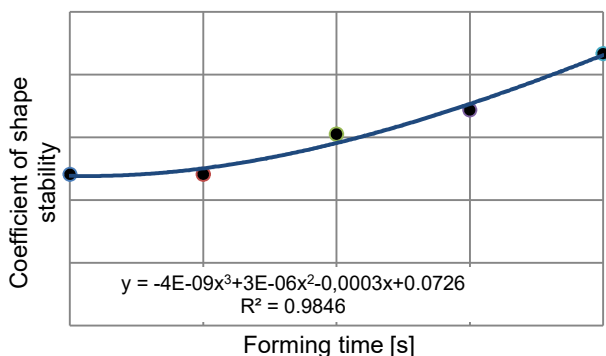
$y = 0.0001x^3 - 0.0062x^2 + 0.0851x - 0.2599$
$R^2 = 0.9868$

Figure 8 Dependence of coefficient of form stability on the formation time for a coat fabric in the study of coat fabrics

$y = -4E-09x^3 + 3E-06x^2 - 0,0003x + 0.0726$
$R^2 = 0.9846$

Analysis of the influence of each factors on the process of forming textile materials, which were studied, showed that the curves of dependence of shape stability coefficient on the main factors have the same character. Considering influence of a speed on the parts formation from textile materials by centrifugal method (Figure 4), there is

a decrease in the coefficient of form stability with increasing factor. That is, the shape of the part is improved. Increasing the values of rotational speed leads to an increase in the forming forces acting on external and internal connections of textile material. This improves deformation properties of the studied fabrics, and confirms theoretical assumptions.

The graphical dependences (Figure 5) showed that increase in the volume of LAWE is accompanied by decreasing in the coefficient of shape stability. Thus, with increase of this factor the formation process is more intensive, due to increase of moisture content of textile material, which improves its deformation properties. It is determined that with increasing a forming time there is an increase in the coefficient of form stability and deterioration of the quality of formation operation (Figure 6). The results of experimental studies allow to conclude that the factors of centrifugal forming process - the speed, volume of LAWE and forming time significantly effect on the quality of molded part.

As can be seen from the graphs (Figures 4-6) and regression equations (Table 3), the relationships between input factors and a coefficient of shape stability are nonlinear and do not clearly indicate the importance of influence of parameters on this process. Therefore, a multifactorial experiment is required in the future. The analysis of one-factor dependences indicated that it is possible to narrow the ranges of the studied factors for a multifactor experiment. Narrowing of ranges is caused by inexpediency of use of process outside certain limits. This is due to the fact that the lower indicators of the selected parameters do not provide the appropriate quality, and higher indicators are not rational to use due to increased energy consumption with a slight increase in quality.

According to the graph (Figure 4) by changing the rotational speed of 6 to 14 s^{-1} it is possible to reject a range of values up to 8 s^{-1}, because the experimental equipment has not yet gone into operation and LAWE is moving chaotically. This is not a managed process because after 13 s^{-1} increased energy consumption. As the graphical dependence shows (Figure 5), analyzing the influence of LAWE volume, the range of values up to 14 l was rejected and after 19 l. The area of studied factor was narrowed from 13 to 18 l. The studied range of formation time (Figure 6) indicates that it is possible to reject the range of values up to 90 s and from 150 s, because with increasing duration of formation the quality does not improve. To perform a multifactorial experiment, were used the calculation matrices of the second-order rotatable plan, five levels of variation of parameters that effect on the forming process. The range of values of input parameters was adjusted on the basis of previous studies and formed the basis of a multifactorial experiment (Table 5).

Table 5 Levels and intervals of factors variation for study of coat fabrics

Levels of variation	Parameters of forming process		
	Frequency speed n [s^{-1}] (x_1)	LAWE volume V [l] (x_2)	Forming time t [s] (x_3)
+1.68	13	19	150
+1	12	18	138
0	10.5	16.5	120
−1	9	15	102
−1.68	8	14	90
Interval of variation	1.5	1.5	18

According to the results of experimental data of studied fabrics, a special program "Planning experiment" was used to determine the coefficients of regression equation, as well as to derive the regression equation of mathematical model of the centrifugal forming process according to the specified parameters. According to the selected plan of the experiment, the number of experiments was obtained $N = 15$, number of input factors $n = 3$, the number of repetitions of each experiment $k = 3$. On the basis of experimental researches of centrifugal formation of coat fabrics received the regression equation of mathematical model of process in the coded form:

$$y = 0.0601 - 0.0096x_1 - 0.0035x_2 + 0.0014x_3$$
$$+ 0.0017x_1x_2 - 0.0094x_1x_3 + 0.0071x_2x_3 \qquad (20)$$
$$+ 0.0053x_1^2 - 0.0030x_2^2 + 0.0188x_3^2$$

To determine the weight of parameters of process a centrifugal formation of coat fabrics was substituted a values of factors x_1, x_2, x_3 (+1.68; 0; -1.68) in the regression equation (20) with the stabilization of two factors at zero level. Based on this, one-factor graphical dependences are built $K = f(x_1)$ and defined the influence of each of the factors on original function, that is, the coefficient of form stability.

The analysis of the obtained results shows that an indicator of form stability coefficient K is greatest influence by the duration of formation ($K = 0.0538$). The value of duration x_3 is at a minimum level -1.68. The next most important parameter is frequency speed, at maximum value +1.68, a coefficient of stability of which is $K = 0.0566$. Indicator value $K = 0.0575$ is achieved when the volume of LAWE is at the maximum level +1.68.

After conducting, an experimental research in one-factor and multifactor experiments were rationalized parameters of the process of hydro-centrifugal forming method. As a criterion for optimizing a process of centrifugal formation of textile materials, the coefficient of form stability was chosen. It is given by a function that goes to the minimum value. To determine the extreme (minimum) value of the original function of mathematical model, the equations are differentiated for each independent variable. The construction of response surfaces of the coefficient of shape stability from the input

parameters (speed, volume of RARS and time of formation) gives the opportunity to get a clear idea of patterns of change of this optimization criterion [39].

For this purpose, the analysis of response functions was performed and was carried out rationalization of formation process. A task of rationalization was to find the values of factors that belong to the range of permissible values $x_i \in$ [-1.68; 1.68], at which output parameter has minimum value and condition is fulfilled $y \le 0.2$.

Analyzing the nature of response surface of stability coefficient of from parameters of frequency of rotation and volume of water with the stabilization of the factor of formation time at the level $x_3 = 0$ ($t = 120$ s) in the study of coat fabrics, following conclusion can be drawn: the best quality of formation occurs at values of parameters of rotation frequency $n = 13$ s^{-1} and LAWE volume $V = 19$ l, as evidenced by the minimum value of optimization parameter (coefficient of stability) $K = 0.055$ (Figure 9).
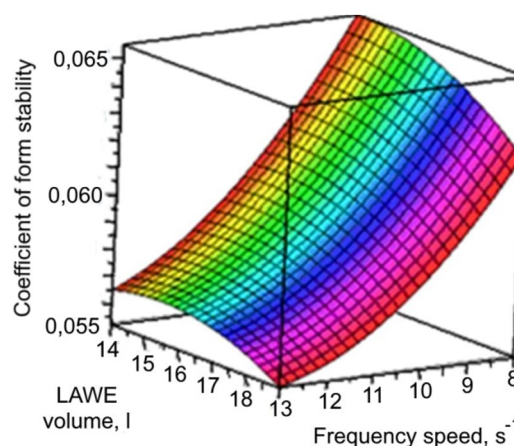

Figure 9 Dependence of response function of frequency speed and LAWE volume at $x_3 = 0$ ($t = 120$ s) in the study of coat fabrics

When analyzing the response surface of LAWE volume and formation time when stabilizing a speed at the level $x_1 = 0$ ($n = 10.5$ s^{-1}) for coat fabrics, it is determined that the most stable form is obtained at the following values of parameters – forming time $t = 90$ s and LAWE volume $V = 19$ l, as indicated by the minimum value of stability coefficient $K = 0.050$ (Figure 10).

Considering the nature of response surface of frequency speed and formation time at $x_2 = 0$ ($V = 16.5$ l) for coat fabrics, it is possible to draw a conclusion about optimal modes of formation to achieve the best quality of forming part, which constitute $t = 90$ s and $n = 12$ s^{-1} when the value of the optimization criterion $K = 0.053$ (Figure 11).

The graphical dependences of response function on Figures 9-11 reflect the complex influence of input parameters of centrifugal forming method on the coefficient of form stability. The optimal values of the response functions are represented by minimum that is declines of surfaces. Analysis of these graphic illustrations makes it possible to state that the speed, volume of LAWE and formation time significantly effect on the value of quality indicator of forming process of a coat fabric by centrifugal method.
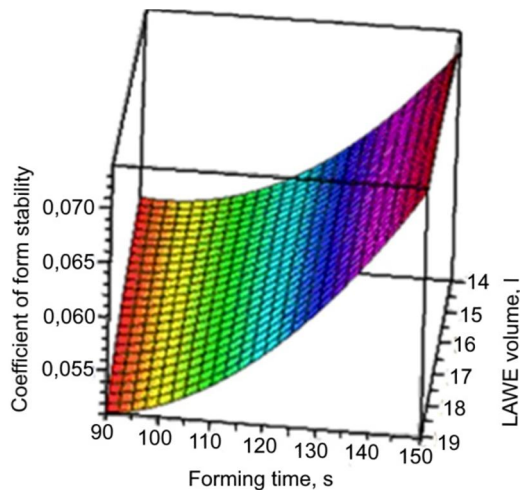

Figure 10 Dependence of response function of frequency speed and LAWE volume at $x_1 = 0$ ($n = 10.5$ s^{-1}) in the study of coat fabrics
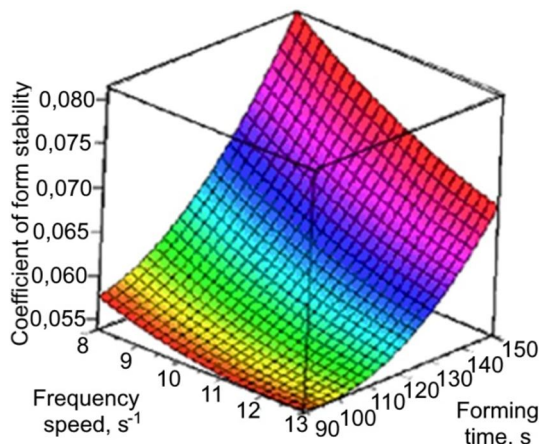

Figure 11 Dependence of response function of forming time and of frequency speed at $x_2 = 0$ ($n = 16.5$ s^{-1}) in the study of coat fabrics

Therefore, the rational parameters of the process of centrifugal forming in LAWE for this fabric are: frequency speed $n = 12.5$ s^{-1}; LAWE volume $V = 19$ l and forming time $t = 90$ s, as evidenced by the minimum value of the coefficient of stability K.

4   CONCLUSIONS

A hydro-centrifugal method of forming three-dimensional parts of women headwear has been developed by replacing the working environment of steam with LAWE. To implement this method the experimental equipment was developed for forming the details of three-dimensional shape of hats and the method of experiment conducting.

A physical model of the hydro-centrifugal forming method has been developed. The choice of factors for the formation process and materials for research is substantiated. The choice of the method of assessing quality of forming process using the value of coefficient of shape stability is substantiated.

Investigated the influence of main input factors on the quality of formation of headwear parts: for fabrics frequency speed $n = 8$-13 s^{-1}; LAWE volume $V = 14$-19 l and forming time $t = 90$-150 s. As a result of statistical processing data of multifactorial experiments the adequate mathematical models of the second order of formation process were obtained. For each fabric were identified rational parameters of the centrifugal forming process, in which the best quality of formation is achieved and they are: for coat fabric frequency speed $n = 12.5$ s^{-1}; LAWE volume $V = 19$ l and forming time $t = 90$ s with $K = 0.053$.

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